TN 295
.U4

No. 8800

1979

IC 8800

Bureau of Mines Information Circular/1979

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299

Mine Power Systems Research

(In Four Parts)

2. Grounding Research

UNITED STATES DEPARTMENT OF THE INTERIOR

United States, Bureau of Mines

Information Circular 8800

Mine Power Systems Research

(In Four Parts)

2. Grounding Research

Compiled by Staff–Mining Research

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES
Lindsay D. Norman, Acting Director

TN 295
.U4
no. 8800
1979

This publication has been cataloged as follows:

United States. Bureau of Mines

Mine power systems research (in four parts) : 2. Grounding research / compiled by staff—Mining Research. [Washington] : U.S. Dept. of the Interior, Bureau of Mines, 1979.

78 p. : ill. ; 27 cm. (Information circular - Bureau of Mines ; 8800)

Includes bibliographical references.

1. Electricity in mining. 2. Mining machinery - Electric equipment. 3. Electric currents - Grounding. I. Title. II. Title: Grounding research. III. Series: United States. Bureau of Mines. Information circular - Bureau of Mines ; 8800.

TN23.U71 no..8800 622.06173

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MINE POWER SYSTEMS RESEARCH

(In Four Parts)

2. Grounding Research

Compiled by Staff–Mining Research

ABSTRACT

This Bureau of Mines publication contains five papers pertaining to the effective grounding of mine power systems, as follows: Ground-check monitor types and safety characteristics; ground wire monitors for surface coal mines; ground bed design and measurement; electrical ground rod corrosion; and a continuous ground bed resistance monitor.

INTRODUCTION

The Federal Coal Mine Health and Safety Act of 1969 required that all resistance-grounded systems include a fail-safe ground check circuit to monitor continuously the continuity of the grounding circuit. Problems occurred when this regulation was implemented; the major problem area was intermachine arcing caused by the asymmetry of the new type G-GC cables used with the ground monitors.

As an outgrowth of this problem, the Bureau of Mines initiated a major research program to investigate ground check monitors and grounding systems. In the early stages this program was limited to underground grounding systems; however, as problems arose in the monitoring of grounding circuits in surface mines, research was also conducted on surface mine ground systems. Five papers resulting from work done at West Virginia University under contract to the Bureau are presented herein.

The first two papers discuss the roles of ground check monitors in surface and underground coal mines. The first paper discusses various monitors used in underground coal mines and attempts to show how different monitoring configurations affect the monitoring. The second paper discusses the problems of monitoring a high-voltage grounding circuit with emphasis on the lightning transient. This paper also contains comments on several monitors tested in the laboratory.

The next paper describes a device that monitors the grounding circuit from the point where the ground check monitor terminates. This instrument continuously monitors the resistance of the ground bed. The paper describes the device and field tests conducted at operating mines.

The fourth paper develops an analogy between a rubber sheet and the design of a ground bed. The rubber sheet analogy allows the designer to better grasp the concepts of touch and step potentials.

The last paper describes a relatively new area of grounding research--corrosion. This paper describes the process of corrosion in ground rods and gives test results for some commonly used ground rods.

All five papers are intended to provide information that can be used immediately by mine personnel, manufacturers of equipment, and the Mine Safety and Health Administration (MSHA). Throughout this report, reference to specific components or trade names is made for information only and does not imply endorsement by the Bureau of Mines.

GROUND CHECK MONITOR TYPES AND SAFETY CHARACTERISTICS

by

R. L. McConnell[1] and Sivalingam Jeevan[2]

ABSTRACT

Ground check monitors may be made in several configurations. Each type has unique characteristics and provides different safety attributes when applied to different mine situations. In this paper, the monitor types are discussed in relation to the mine situations. It is shown that the selection of the monitor type can have a significant effect on the safety of the resistance grounded power system. The options are discussed, and the conclusion is drawn that only one monitor configuration can provide maximum safety. Unfortunately no monitors of this configuration are presently available. In addition, when the monitor capabilities and ground wire configurations are considered as a system, it can be shown that certain configurations will lead to maximum safety. This work was supported by U.S. Bureau of Mines grant G0144138.

INTRODUCTION

Developing ground check monitors at first looked straightforward, and the initial devices were rather simple. When they were placed in service, however, the real magnitude of the problem began to be evident. Following several months of redesign and testing, ground check monitors slowly emerged that were capable of monitoring the integrity of the ground wire under the adverse conditions existing in the portable power cables in underground coal mines. This second generation of monitors has received MSHA acceptance, and several are commercially available.

The monitors accepted by MSHA go through a stringent laboratory test and a field test before acceptance. Many of these monitors have several months of acceptable field operation and seem to be acceptable to the mine operators. Thus, the primary part of the ground check monitor program is being satisfied.

Under a research program funded through the Bureau of Mines, the safety characteristics of the various types of monitors have been studied, and some problems of a secondary nature have become apparent. For example, it has been found that certain monitor configurations are inherently safer than others. These secondary problems are the subject of the following discussion.

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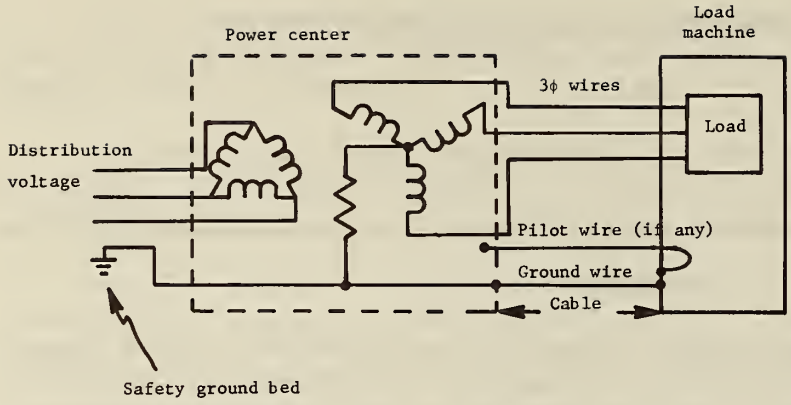


FIGURE 1. - Typical resistance grounded power system.

THE RESISTANCE GROUNDED SYSTEM

To understand the monitoring problems, a thorough understanding of the resistance grounded system is required. A typical resistance grounded power system is shown in figure 1. The distribution supply is brought into the power center to the primary of the transformer. The neutral of the y-connected secondary is connected to the safety ground and the ground wire through the safety ground resistor. For low-voltage systems, this resistor must limit phase-ground fault currents to 25 amp or less. The circuit diagrams are identical for medium- and high-voltage system; only the voltage and current requirements are different. The safety grounded resistor reduces the fire hazard during fault conditions. If a ground fault occurs, a ground-fault interrupter opens a set of contacts in series with the undervoltage release (UVR) to trip the circuit breaker. An excellent discussion of the safety grounded system has been written by Gary Powell (3).[3]

The safety of this system depends upon the integrity of the ground wire between the load machine frame and the connection to the safety grounded resistor. If the ground wire is open when a phase-machine frame fault occurs, a person touching the machine frame can receive a lethal shock. This may seem an unlikely event, but since the ground wire normally carries no current, operations can continue for a considerable length of time with an undetected break in the ground wire. Thus, MSHA has decreed that all equipment powered through low-voltage trailing cables shall be protected with ground check monitors. Monitoring is to be done in such a way that the circuit breaker is tripped by the UVR if the ground wire is opened; or if an alternate (parallel) conduction path shunts a broken ground wire, the circuit breaker is opened if the total circuit impedance rises to a value that would allow 40 volts on the machine frame under a ground fault condition.

The value of the trip impedance that must be detected by the monitor will be a function of the neutral grounding resistor. As an example, a 480-volt system has 277 volts line-to-neutral. With a 25-amp short circuit current limit, the safety ground resistor is 11.08 ohms. To limit the machine frame voltage to 40 volts during a fault, a series resistance as low as 1.87 ohms must be detected.

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

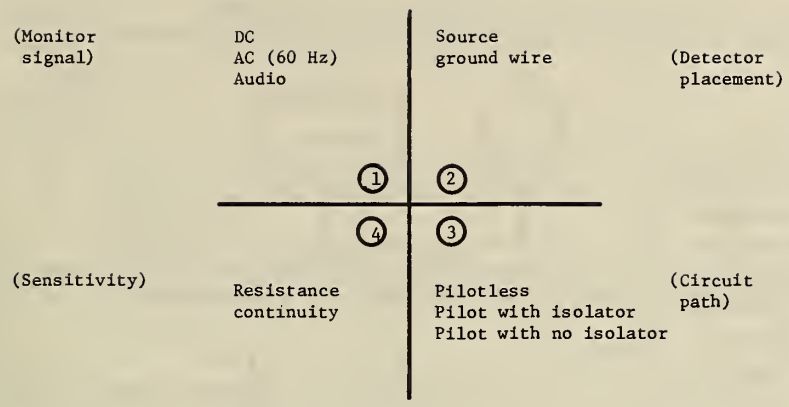


FIGURE 2. - A method of monitor classification. Any monitor is characterized by one descriptor from each group; for example, AUDIO-SOURCE-PILOTLESS-CONTINUITY.

MONITOR CLASSIFICATION

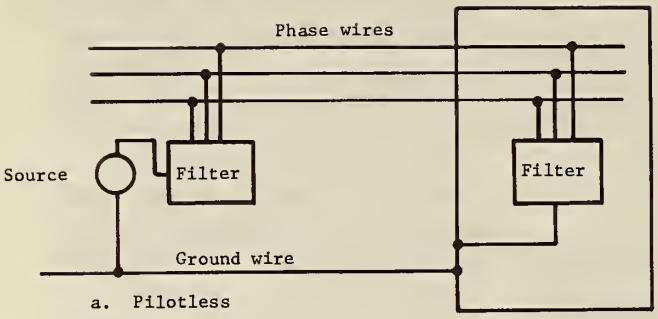
Ground check monitors may be classified in a number of different ways. One method is shown in figure 2; other methods are discussed elsewhere (1-2). With this classification scheme, there are 36 possible configurations. For most of the problems discussed and characteristics required, only two categories need be considered at any one time.

The monitor signal may be either 60 Hz ac, dc, or audio. An audio signal is considered to be any ac signal that is not 60 Hz and can have any waveform. The audio signal is the most often used, because both dc and ac stray currents and potentials appear in the grounding system, and because the pilotless systems require the audio signal for transmission on the phase wires.

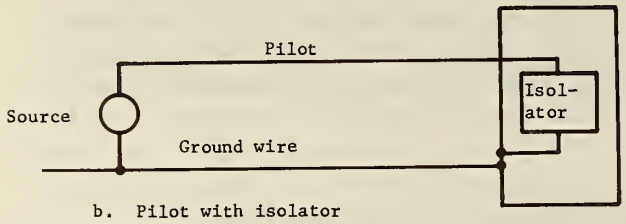
A monitor is considered to be the resistance type if it is sensitive to a low value of resistance, normally 10 ohms or less; the sensitivity is usually adjustable. The monitor is the continuity type if the trip point is greater than 10 ohms; the trip point of continuity monitors is not usually adjustable.

Basically, all monitors must pass current around a loop. The loop consists of the ground wire and either the pilot wire or the phase wires. The three circuit paths are shown in figure 3. For the pilotless case, the filters are used to couple the monitor signals to the phase wires at both ends of the loop. For the pilot-wire monitors, an isolator may be used to tune the loop to the monitor frequency. The isolator provides a means of detecting a pilot-ground-wire short, as discussed later. When no isolator is used, the pilot wire is simply connected to the machine frame.

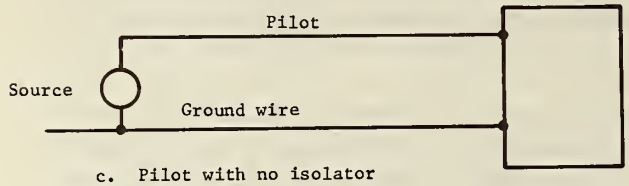
The basic distinction between the detection schemes is the placement of the detector. Three configurations are shown in figure 4. The first two schemes measure voltage or current at the monitor source, either in the pilot wire or the phase wire loop. These are classified as source detectors. The third scheme has a shunt detector in the ground wire. This method actually measures current flow in the ground wire. For the purpose of this discussion, the two source detector methods are considered equivalent because ground wire continuity is the object of the measurement, not pilot wire or phase wire continuity.



a. Pilotless

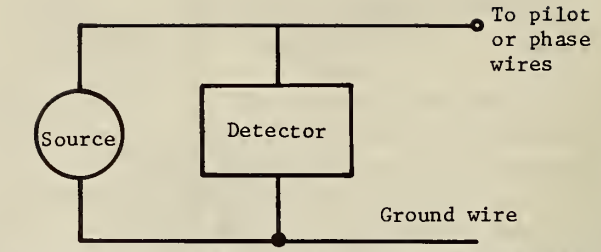


b. Pilot with isolator

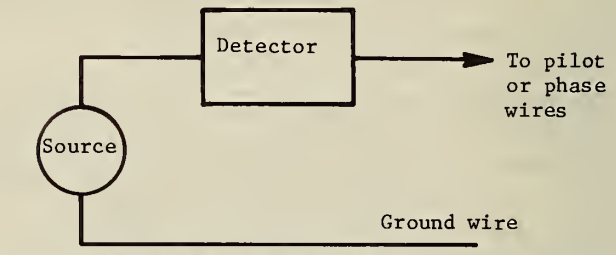


c. Pilot with no isolator

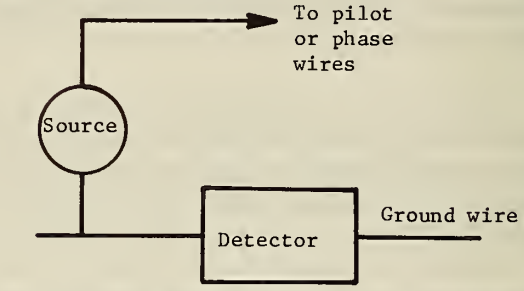
FIGURE 3. - The three circuit paths that can be used in monitors.



a. Potential detector measures voltage between pilot (or phase) and ground wire.



b. Current detector measures monitor current in pilot or phase wires



c. Shunt detector in ground wire measures ground wire current.

FIGURE 4. - Detector placement.

A listing of commercially available monitors is given in table 1. The classification of each monitor is given along with a single character designation for later reference. Four of the monitors are capable of being connected with or without a pilot wire. A subscript is used to distinguish between the two cases.

TABLE 1. - Commercial monitors, including the designations used in this paper, and the classification of the monitors

Designation	Source	Classification			
		1	2	3	4
A	American Mine Research Inc.	Audio	Ground wire	Pilotless....	Continuity.
B	Apparatus Engineering Co...	AC...	Source.....	Pilot with no isolator.	Resistance.
C	Control Products, Inc.....	AC...	...do.....	.....do.....	Do.
D_1	Ensign Electric (Eltron Corp.).	Audio	Ground wire	.....do.....	Continuity.
D_2	.....do.....	Audio	...do.....	Pilotless....	Do.
E	Ensign Electric Div., Harvey Hubbell, Inc.	AC...	Source.....	Pilot with no isolator.	Resistance.
F_1	Femco Division, Gulton Industries, Inc.	Audio	...do.....	.....do.....	Continuity.
F_2	.....do.....	Audio	...do.....	Pilotless....	Do.
G	Line Power Manufacturing Corp.	AC...	...do.....	Pilot with no isolator.	Resistance.
H_1	Ohio Brass Co.....	Audio	Ground wire	.....do.....	Continuity.
H_2	.....do.....	Audio	...do.....	Pilotless....	Do.
I	Pemco Corp.....	AC...	Source.....	Pilot with no isolator.	Resistance.
J	Shaffer Equipment Co.....	AC...	...do.....	.....do.....	Do.
K	Electro Manufacturing Corp.	AC...	...do.....	.....do.....	Do.
L_1	Kaiser Aerospace and Electronics Corp.	Audio	...do.....	Pilot with isolator.	Continuity.
L_2	.....do.....	Audio	...do.....	Pilotless....	Do.
M	Sasser Electric & Manufacturing Co.	AC...	...do.....	Pilot with no isolator.	Resistance.

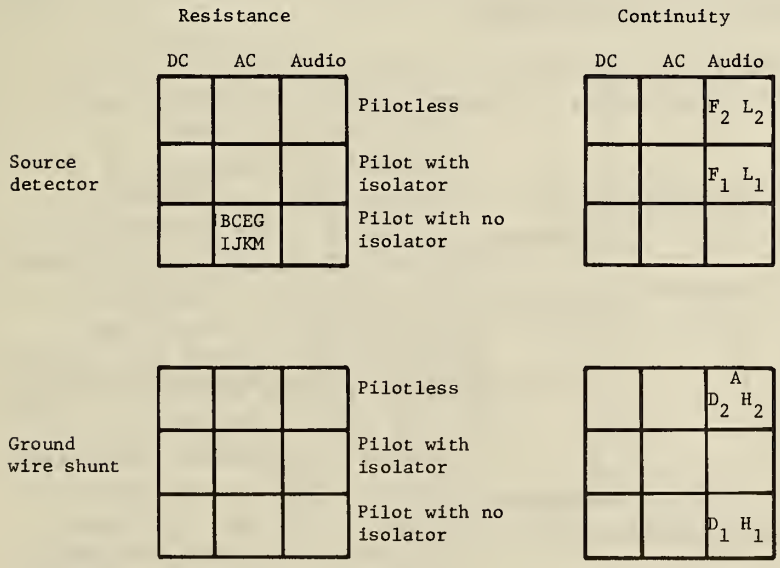


FIGURE 5. - Classification of commercial monitors. See table 1 for key to designations.

Of the 36 possible configurations, only 5 are used. These are shown in figure 5. Note that no dc monitors are available. This is not surprising in view of the prevalence of dc stray currents in underground mines. In addition, no monitors are available that measure resistance and use a ground wire shunt detector. Such a measurement may be difficult to make owing to the large stray currents in the ground wire.

MINE PROBLEMS WITH MONITORS

There are several situations in the monitoring environment that cause or

could cause safety or functional problems with monitors. Some of these problems have no known perfect solution, but some monitoring methods are superior to others under these conditions. Other problems have known solutions but require changes in hardware. These situations should be kept in mind when new installations are being made.

Some of the problems have already been mentioned. Stray current and potential problems are fairly common. Audio monitors are inherently less susceptible to stray current and potential but can also be affected, primarily by saturation of detectors. In addition, filtering can remove much of the stray 60 Hz and its harmonics if the monitor frequency is fairly high. High-frequency monitor signals will limit the length of cables that can be monitored. The fact that several 60-Hz ac monitors have been accepted by MSHA, and that these are the only monitors capable of measuring low impedance, indicates that ac monitors can be useful. However, stray ac potentials can, under the right circumstances, cause false tripping or false hold-in, and false hold-in can be dangerous. It is fairly easy to visualize a situation where a broken ground wire would not be detected because of a stray potential. To remedy this situation, an ac monitor could go through a checking routine periodically where the monitor signal is removed and a trip signal received momentarily.

Transients are also observed in many situations. To overcome this problem, the manufacturers are allowed to provide up to a 250-msec time delay. It should be noted that this delay is a compromise on safety but appears necessary at this time in order to have a workable system. None of the configurations appear inherently more immune to the effects of transients. Designs utilizing only passive components are less likely to be damaged by large transients, however. Transient protection should be built in as part of all monitors using solid-state devices.

Pilot-to-Ground Shorts

Another potential hazard is a pilot-wire-to-ground-wire short circuit. Where the pilot wire is used for monitoring, a short between the pilot and ground wires leaves an unmonitored section of the ground wire, as shown in figure 6. The simple expedient of placing an isolator (any component the monitor is capable of detecting) between the pilot and ground wires at the machine frame will enable the monitor to detect the short. The placement of the isolator is shown in figure 7. Detection of the short assumes, however, that the monitor can detect the absence of the isolator.

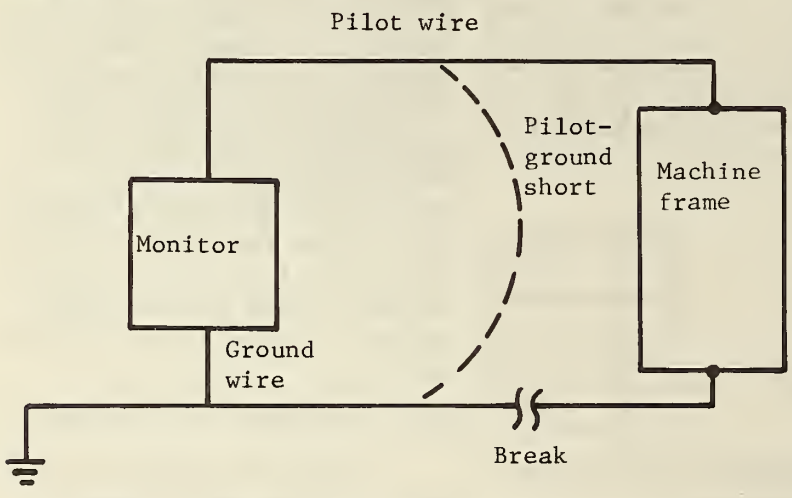


FIGURE 6. - Pilot-to-ground wire short will leave a section of the ground wire unmonitored.

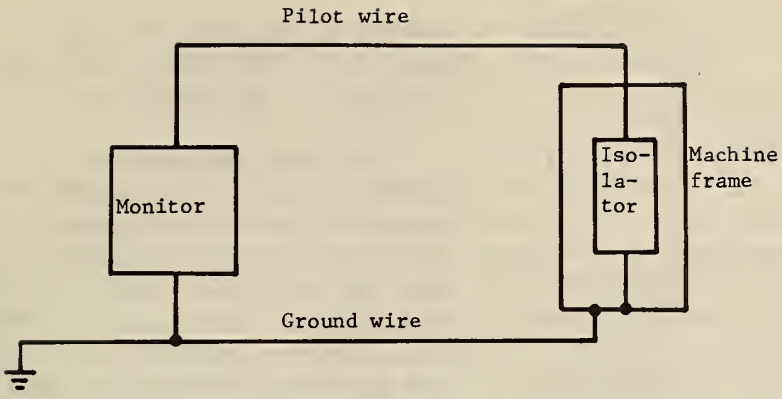


FIGURE 7. - Isolator placed between the pilot and ground wires at the machine frame will normally be in the monitoring circuit. Thus the monitor can be made to detect a pilot-to-ground wire short.

There are 12 monitors accepted for a pilot wire configuration. Of these only two--F and L--require the use of an isolator between pilot and ground. Thus, only these two monitors provide the additional safety characteristics of detecting a pilot-to-ground short.

Of course the pilotless monitors do not suffer from this hazard. For this reason, and because the asymmetric type G-GC cables are known to produce potentials capable of intermachine arcing, the pilot wire cables should probably be phased out. With adequate pilotless monitors, the pilot wire serves no useful purpose in ground check monitoring.

Parallel Paths

One of the most pervasive problems in monitoring is the parallel path. The parallel path shunts the ground wire, and if it is of low resistance, it may mask a break in the ground wire. A simple parallel path shunting a broken ground wire is shown in figure 8. While this situation does satisfy the original premise that the machine frame is to be connected by a low resistance to the ground resistor, it is not entirely satisfactory in that the path resistance can suddenly increase to a high value, upon occurrence of a large surge of a fault current.

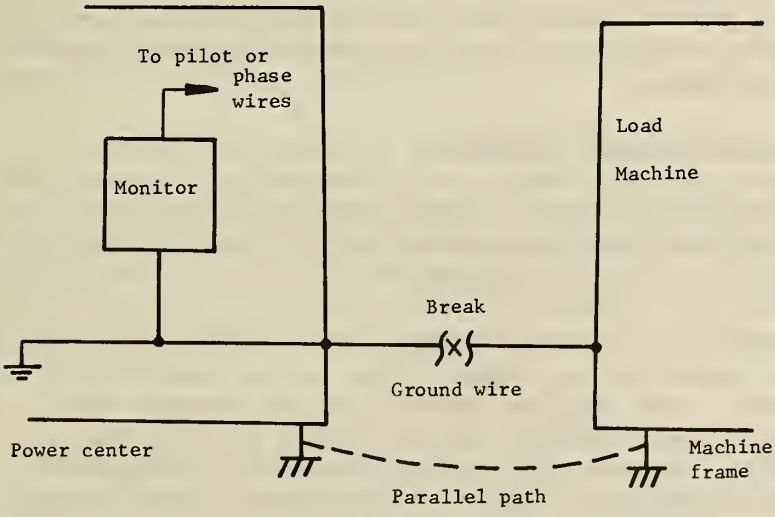


FIGURE 8. - Simple parallel path between the power center frame and load machine frame shunts a break in the ground wire.

There are two approaches in dealing with parallel paths. The resistance of the total ground connection may be measured as allowed by MSHA rules; here, the major difficulty is the low value of resistance that must be detected. The other method is to detect current in the ground wire using ground wire detector-type monitor; the greatest difficulty with this method is that a very low resistance parallel path may shunt so much current from the ground wire that its integrity

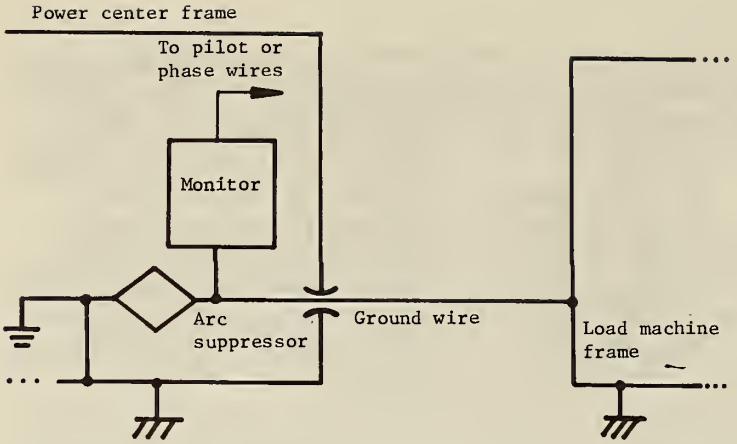


FIGURE 9. - Arc suppressor may be used to isolate the ground wire from the earth at the power center.

cannot be detected by the monitor. The result will be a false or nuisance trip.

In the presence of parallel paths, the source detector monitor must measure the effective resistance of the total ground connection. This will allow a machine to operate with the ground wire open, a situation of marginal safety. A phase-to-ground fault will not cause a high voltage on the machine frame as long as the parallel path impedance is low. The ground fault interrupter will trip at the circuit breaker. A failure of the circuit breaker of the ground fault interrupter will allow a high voltage on the machine frame if the parallel path resistance rises. In other words, the safety system may fail in an unsafe condition. The ground check monitor can be forced to monitor the ground wire by placing an arc suppressor or other similar device in the ground wire between the monitor connection and the safety ground resistor connection, as shown in figure 9. Both inductive and diode-type arc suppressors have been used. This allows the ground wire to be effective isolated from a parallel path at the power center end. Under fault conditions, the arc suppressor adds a small but limited voltage to the voltage drop in the ground wire. The monitor trip impedance should be correspondingly reduced.

It is interesting to note that in order to eliminate a potential hazard, another has been added. The arc suppressor is in series with the ground wire and is not monitored. However, the arc suppressor is not likely to fail because it is mounted inside the power center where the device and its connections are not subject to abuse. Neither of the two possible hazards is severe, but neither situation is ideal.

The ground wire detector-type monitor represents a trade-off between a fail-safe monitoring situation and the possibility of false trips. Again, the arc suppressor may be used to isolate one end of the ground wire from parallel paths, as shown in figure 9. This will eliminate the false trips, but again at the peril of potential failure in the arc suppressor.

With these two types of monitors, there are three possible results with parallel paths: an unmonitored ground wire, false trips, or an unmonitored arc suppressor in the ground wire. The monitor classification scheme used earlier assumes that all monitor signal sources are connected between the ground wire and the pilot or phase wires. One monitor, however, provides an alternative (D_2). This monitor, when used without a pilot wire, requires two current transformers, a sender and receiver, on the ground wire. Thus, if the ground wire is connected, there will be current in the ground wire regardless of any parallel paths. A similar arrangement could easily be implemented for pilot-type monitors, but none are presently available.

It is also interesting to examine the parallel path problem with respect to the resistance sensitivity of the monitors. It should be noted here that all of the 60-Hz ac monitors are of the resistance type and all of the audio monitors are used without arc suppressors. Sensitivity to low impedance is required in order to handle parallel paths. All of the resistance monitors except monitor K are approved for this case. Monitor K requires the use of an arc suppressor. When arc suppressors are used, only continuity sensitivity is required, but resistance types are certainly satisfactory. All that is required is that the monitor detect an open ground wire. The ground wire detectors can inherently detect an open ground wire and do not necessarily need an arc suppressor. Monitor D can be used with or without an arc suppressor. Monitors H_1 and H_2 use a special shunt in the ground wire, which also acts as an arc suppressor.

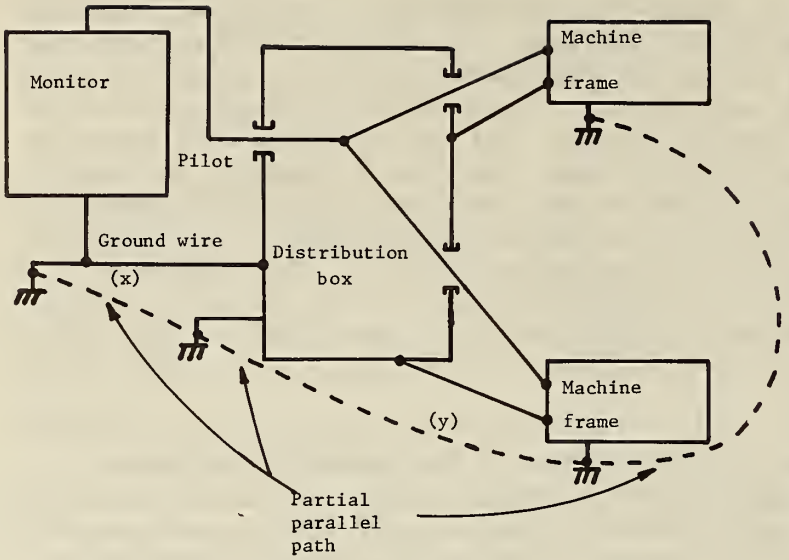
The monitoring rules are not very strict. The intent of the safety ground resistor is to limit the current during a ground fault. To limit the machine frame voltage to 40 volts during a ground fault, the ground connection resistance must be limited to 1.87 ohms if the fault current is limited to 25 amp. The continuity monitors are only sensitive to a few tens of ohms, however. If, for example, the ground wire resistance were 10 ohms, which would not trip a continuity monitor, the machine frame would be at 130 volts during a ground fault. Thus, it is clear that the resistance monitors are superior in this respect. Only very low resistance settings should be tolerated.

From the preceding discussion concerning pilot wires and parallel paths, several recommendations have been made. These result in the conclusion that only one type of monitor shares all of the superior characteristics. Unfortunately this monitor is not available. A configuration like that of monitor D_2 can eliminate parallel path problems, and it should be of the resistance type. Also since pilot wires should be eliminated, only pilotless monitors are required. This in turn indicates audio source signals. Thus the monitor with the greatest potential for safety is the audio-pilotless-resistance-type monitor with both source and detector in the ground wire. In addition, only symmetric cables should be used so that arc suppressors can be eliminated.

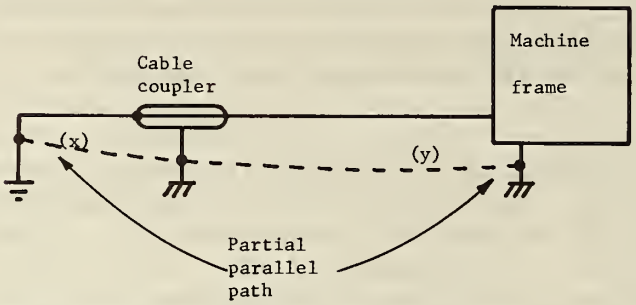
Partial Parallel Paths

Another form of the parallel path problem arises when the ground connection is made partly through the earth and partly through the ground wire. These partial parallel paths arise when more than one machine is connected to the ground wire or when a cable coupler or control box is connected at an intermediate point in the ground wire. Both configurations are shown in figure 10.

The partial parallel path problem appears to be somewhat intractable with present monitoring techniques. The partial parallel paths indicated by (x) in figure 10 can be handled in the same manner as the full parallel path and do not pose any particular problem. The other paths, marked (y), pose the real problem. In these cases monitoring will be done through the earth path, and the system may operate with an open ground wire. Obviously these cases must



a. Multiple machine frames connected to the ground wire.



b. Cable coupler connected to the ground wire.

FIGURE 10. - Partial parallel paths.

be monitored with a resistance-type monitor. Monitors with the detector in the ground wire again provide the greatest safety in these cases. The previously specified monitor seems best.

It will be observed that a break in the ground wire connecting one of the two machines in figure 10a would be shunted by the ground wire to the other machines. In an effort to eliminate this problem, the multiple machine frames are often connected as shown in figure 11. It is then observed that this configuration is electrically equivalent to the circuit in figure 10b. Multiple machine frames are connected at intermediate points along the ground wire, and partial parallel paths can occur.

A further problem can occur in this case. An intermediate frame can become isolated from the ground wire through loose or corroded connections, but the monitor still may measure a low-resistance ground connection through a partial parallel path. Then a fault occurring in the isolated frame places a high potential on that frame. The only apparent solution to this problem is a monitor that can distinguish between the various machine frames. This will undoubtedly involve placing some distinguishable device on each machine frame in the monitoring path. The partial parallel path problem still remains. Either circuit configuration can be monitored this way.

Any attempt to force monitoring through the ground wire by isolating the ground wire from the machine frame with some device like an arc suppressor will immediately cause the same dilemma as was caused by the arc suppressors at the power center end. These isolators would not be monitored. More thought needs to be given to this case. Perhaps a solution can be found that will not involve a compromise. The only completely satisfactory (but impractical) method at present is to monitor each section of ground wire separately.

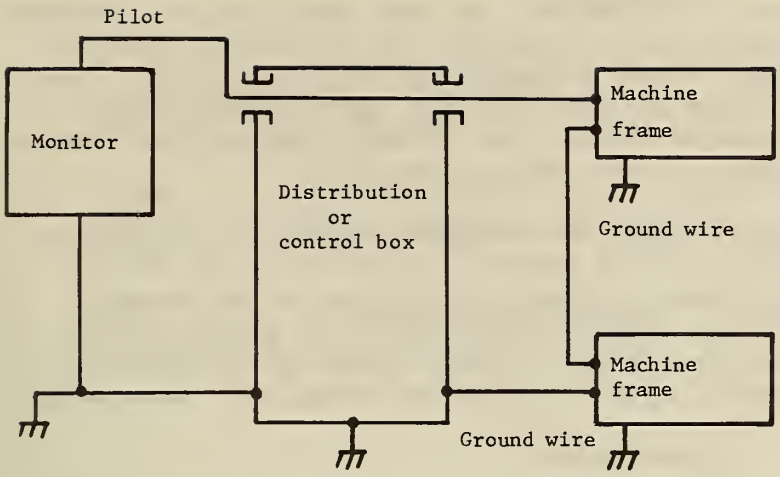


FIGURE 11. - Serial connection of machine frames to ground wire to improve monitoring.

The inline coupler, however, deserves special treatment. The coupler is connected to the ground wire since it should be treated as any other machine frame. There generally is not room however, to add a selective-distinguishable isolator between the pilot to ground or phase wire to ground, inside the coupler. Thus, the following alternatives should be examined:

1. The cable coupler can be left as is. This allows partial parallel paths.

2. The coupler could be isolated from earth by special handling or insulation. Similarly it should also be isolated from human contact if its ground connection cannot be monitored. This would probably involve the use of an insulated case.

3. The use of cable couplers could be eliminated. This alternative is the safest but is not always practical; where cable couplers are required, the case should be insulated and installed in such a manner as to prevent ground-wire-to-earth contact.

CONCLUSION

This discussion has attempted to show that different monitoring configurations can have a subtle effect on the safety of the grounded system. The safety characteristics or problems referred to in this discussion go beyond MSHA requirements and are considered to be of secondary importance.

When the ground check monitoring requirement was instituted, a serious safety problem existed. It was at that time prudent to establish monitors as quickly as possible. However, now that more is known about the problem and about monitoring capabilities, it is time to reexamine the entire problem and look at the safety of the entire grounded system. When the system is examined as a whole, it becomes apparent that changes in the system or practices can also improve safety of the system.

One ground monitor configuration stands out as superior. This configuration uses audio signals, is pilotless, is sensitive to low resistance, and has both the source and detector in the ground wire. Unfortunately, such a monitor is not yet available. In arriving at this conclusion, it also became apparent that the pilot wire served no useful function in respect to ground monitoring. In fact, in asymmetric cables, the pilot wire reduces the safety. Thus, it is further recommended that only symmetrical pilotless cables be used.

When partial parallel paths are examined, the same configuration provides the safest condition. The optimum solution has not yet been found, however, for systems with multiple machine frames connected to the ground wire. Cable couplers also contribute to the partial parallel path problem, and as such should be considered another machine frame. Due to space limitations, however, the cable couplers should be either eliminated or insulated.

The discussion in this paper should be considered neither as an endorsement nor as a criticism of any particular monitor, but is intended only to indicate that still more can be done to improve the safety of the grounded system. The opinions expressed are those of the authors and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the U.S. Government.

ACKNOWLEDGMENT

The authors wish to thank Arlie B. Massey of the Beckley Electrical Testing Project of MSHA, Technical Support, for his cooperation in tabulating the monitoring configurations of the commercially available monitors.

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GROUND WIRE MONITORS FOR SURFACE COAL MINES

by

W. L. Cooley,[1] M. M. Hassan,[2] and K. Y. Lee[3]

ABSTRACT

Because power system topographies for surface coal mines are significantly different from those for underground coal mines, the requirements for ground wire monitors for surface systems are somewhat different. This paper analyzes the problems faced by high-voltage ground wire monitors. Based on this analysis, some design requirements for monitors are suggested. Finally, results from laboratory evaluation of some of the commercially available monitors are presented.

INTRODUCTION

There are three essential differences in the power system topographies of underground and surface coal mines:

1. The feeder cables involved in a surface mine system are several thousand feet longer.

2. Since some surface mining equipment (such as draglines) consumes several thousand horsepower), the utilization voltage level is much higher in a surface mine.

3. There is no track haulage in a surface system; hence no dc is used.

In spite of these differences, the monitoring philosophies in the two systems are essentially the same. However, the ground wire monitors for the surface systems have to be more rugged because greater stresses are imposed on them. They should have the capability of monitoring long cable lengths and of withstanding the large voltage transients generated due to lightning strikes.

This paper describes the general layout of some existing surface mine systems. It also highlights the various problems that the monitors should be capable of withstanding. The problem of lightning is considered in some depth, and a statistical evaluation of lightning-induced failures is made. Some design requirements and performance criteria for monitors are also presented. Finally, results are presented from the laboratory evaluation of some of the commercially available monitors.

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REVIEW OF SURFACE MINE POWER SYSTEMS

To study the problems associated with the monitors required a thorough survey of existing surface mine power systems. In this connection trips were made to the Midwest to study the topographies of several existing power systems. The studies revealed extensive use of overhead lines for high-voltage distribution. In some cases the pole lines also carried the safety ground, which terminated into cables before feeding the loads.

The distribution systems of two of the mines visited are described below. These mines have significantly different topographies, one being fairly widespread and the other being fairly small. It is felt that the observations made on these two systems are fairly typical of most midwestern mines.

To preserve confidentiality the mines will be referred to as mine A and mine B.

Power System Layout for Mine A

Mine A was the smaller of the two mines. It consisted of a single pit. Figure 1 shows the power system. Power at 138 kv was delivered to the mine on a pole line. The utility company 138-kv breakers, visible disconnects, lightning arrestor, and metering station were about 200 feet from mine substation, and power was carried on poles between the yards. An unused but energized pole line broke off just before the mine substation and continued for about 2,000 feet. The pole lines were protected with single static wires. Power was transformed to 23 kv at the substation and fed to the mine through SHD and SHD-GC cables in a radial system. The main-trunk cables were 3/0, 1,000 feet per section. The sections were connected through oil circuit breakers or switch houses. Power was delivered to the 145-cubic-yard dragline at 23 kv.

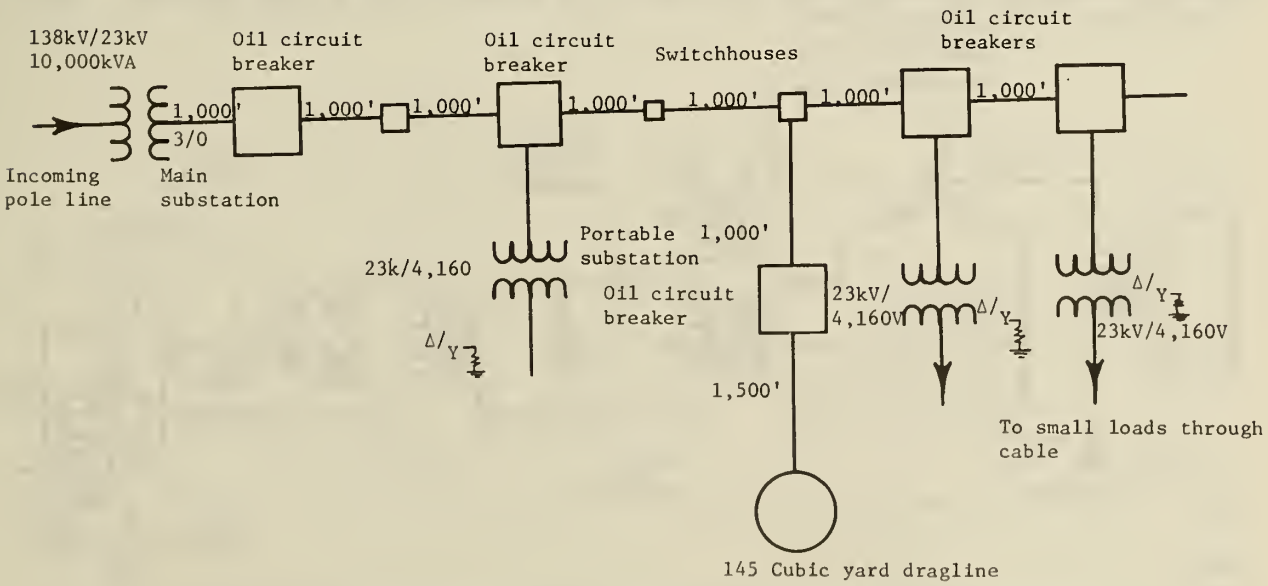


FIGURE 1. - Single-line diagram of the power system of mine A.

All other equipment was fed at 4,160 volts, using portable substations with feed-through. Although not shown on the sketch, the 4,160-volt cable runs were often several thousand feet long.

The 4,160-volt substations were connected Δ-Y, with a transformer-coupled grounding resistor tied to the frame of the unit. Cable grounds and shields were also tied into these frames. All equipment was tied to the safety ground wires in the cables, and all equipment was in metallic contact with the earth. The main substation and several of the secondary substations contained working Atkinson ground wire monitors, but they were only advisory and were not tied into the circuit breaker trip.

Figure 2 shows the interconnection of the Atkinson ground wire monitor to the power system. Power for the monitor is obtained from a control transformer in series with a second transformer. The power was not tied to the station ground. The monitor unit was mounted on a metal panel within the substation, and thus had its frame tied to the station ground. The monitor was connected to the pilot and the ground through small wires (#10 or smaller) which appeared to be insulated for 600 volts.

A series of electrical measurements made at the mine revealed the safety ground bed resistance to be 0.56 ohm. The resistance of the system ground was measured to be 1.38 ohms. The resistance between the station ground and the safety ground was found to be 1.51 ohms.

Power System Layout for Mine B

Mine B consisted of four pits. Each pit obtained its power from one substation close to it. The power between the pits was carried on poles. Figure 3 shows a diagram of these pole lines for 69-kv distribution. The utility company's 138-kv line is shown as a dashed line in the drawing. This

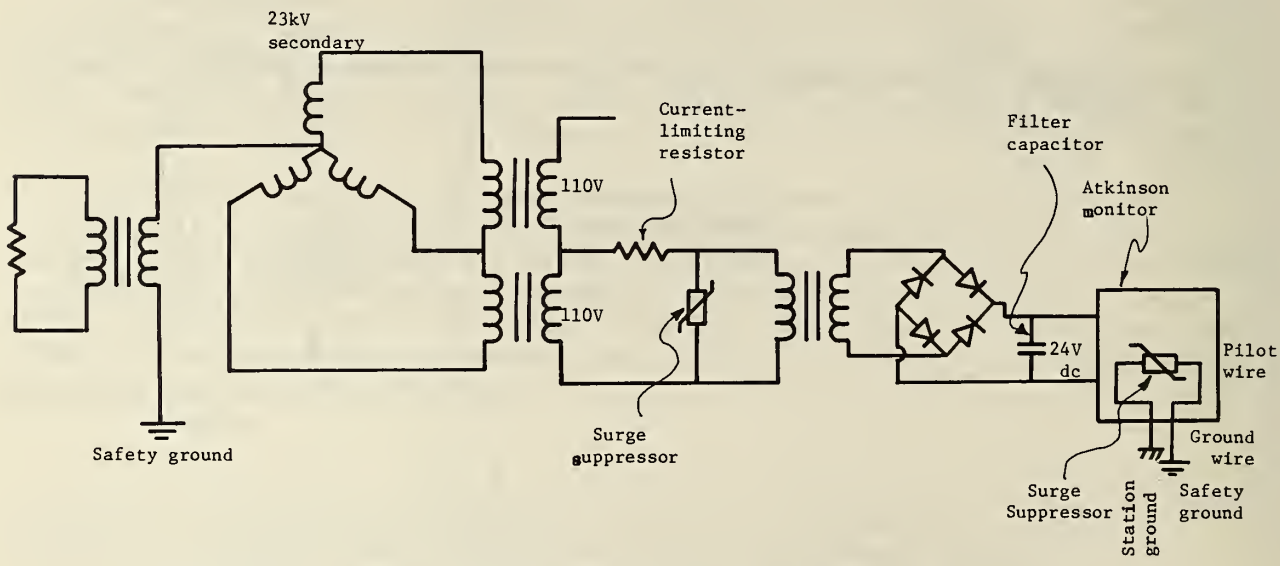


FIGURE 2. - Interconnections of Atkinson ground check monitor, mine A.

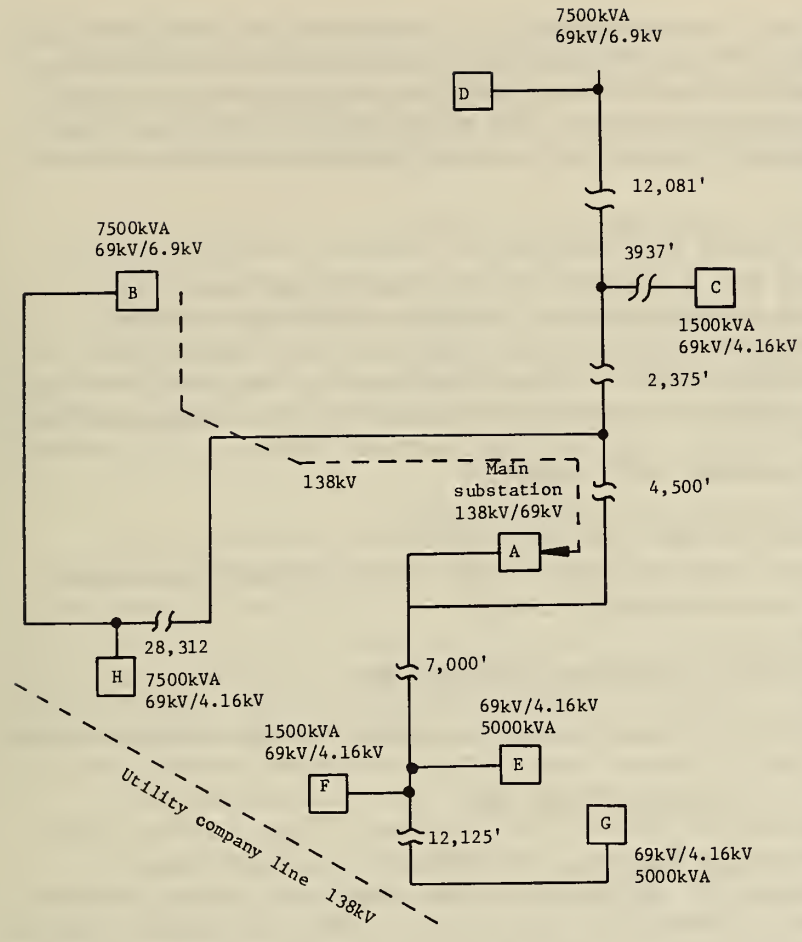


FIGURE 3. - 69-kv distribution pole lines between mining pits, mine B.

power was reduced to 69 kv at the mine's primary substation, located at point A on the drawing. Distribution was then carried out as shown. All lines had an overhead static wire with individual poles being grounded.

Each of the seven secondary substations (B-H) served a network of cables supplying various pieces of equipment in the pits and was installed with its own safety ground bed. The incoming static wires were connected to the station ground bed. The approximate distance between the station and safety ground bed was 50 feet.

The details of the ground wire monitor are shown in figure 4. Unlike mine A, the power supply was referenced to the station ground. The relays, meter, pushbutton, and other components and their mountings was unknown.

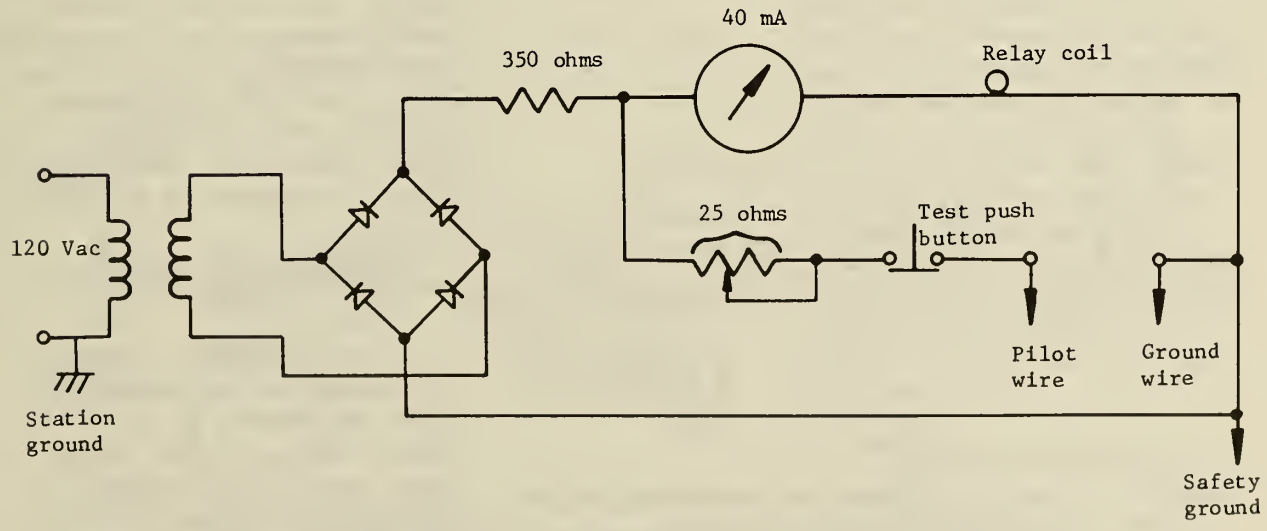


FIGURE 4. - Ground continuity monitoring circuit mine B.

The circuit for the monitor was basically a dc-type device which obtained its power from one phase to ground on the secondary of a single-phase transformer. The 120 volts was applied across one isolation transformer and was converted to dc through a bridge rectifier. The relay coil detected an open circuit along the pilot and ground wires and tripped the main breaker through a capacitor-trip device.

The calculations on the ground bed resistance yielded a resistance of 0.88 ohm for the safety ground and 1.5 ohms for the station ground. Observation of the relative potential between the two grounds showed a distinct 60-Hz waveform between grounds was about 7 volts RMS. A clamp-on ammeter indicated that up to 7 amp RMS flowed into the safety ground bed, and several tenths of an ampere were measured in various connections of the station ground.

PROBLEMS WITH MONITORS

The typical problems faced by monitors for surface applications are enumerated below. Some are the same as might exist in an underground system; others are characteristic of surface systems only.

Induced 60-Hz Voltages and Currents

Owing to the asymmetrical construction of the cable, 60-Hz voltages will be induced in the ground and pilot wires, even though balanced currents may be flowing in the phase conductors. This voltage will be impressed directly across the terminals of the monitor. Due to the extremely long feeder cables involved, this voltage could be substantial. A rough calculation shows induced voltages of approximately 20 mv/1,000 ft per ampere of current in the phase wires. This will amount to about 20 volts for a 5,000-foot cable for 200 amp of current. However, at starting of motors this voltage can rise to approximately 100 volts for a few seconds.

Also, if the machine has a low earth contact resistance (such as a dragline), the voltage induced in the neutral can circulate high currents in the ground wire. The path of current flow is shown in figure 5. This current can also give rise to monitoring problems.

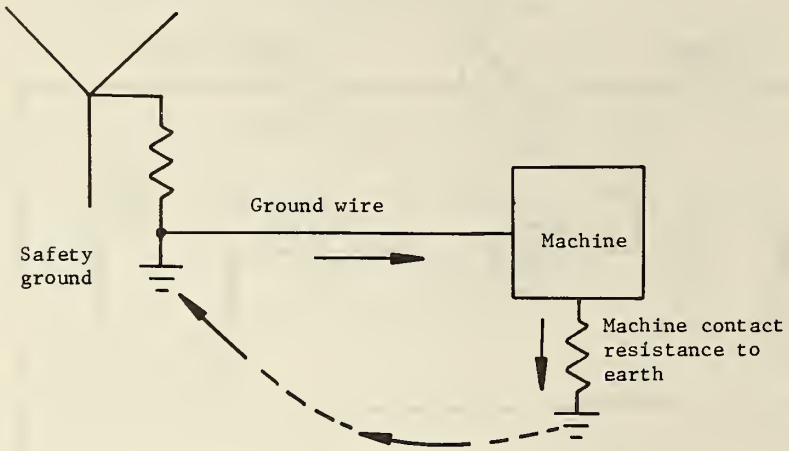


FIGURE 5. - Circuit to illustrate the path of ac stray currents flowing in the ground wire.

Low-Resistance Parallel Paths

Most surface mining equipment has an extremely good connection to the ground owing to the large metal surface in contact with earth. These additional ground paths (parallel

paths) may have a resistance as low as that of the safety ground system itself. Even though these parallel paths do ground the equipment, they may be only temporary and therefore less desirable. Most of the monitors cannot distinguish between a parallel path and the safety ground. They may therefore fail to trip when a parallel path is present even though the ground wire breaks.

Pilot-to-Ground Short Circuits

As a power cable deteriorates from use, it is possible that the pilot wire could become shorted to the ground wires somewhere within a cable. This pilot-to-ground short completes a monitoring loop that would ordinarily be completed only at the machine frame. This problem could be avoided by mounting components on the machine (resistors, filters, etc.) to distinguish between a legitimate monitoring loop and a shorted one.

Extreme Operating Temperatures

Normally, the monitor units are mounted in metal enclosures and left out in the open. Thus on a hot day the temperature inside the enclosure could be quite high. Temperatures as high as 70° C (158° F) are conceivable. Similarly, on a cold day the temperature could go well below freezing. Thus the monitors have to be built for operation within wide temperature limits. There may be difficulty in attaining these limits if solid-state components are used.

Phase-to-Pilot Faults

Because the cable insulation degrades with the passage of time, there is a remote possibility that any of the phase conductors could short to the pilot wire. This type of fault can cause monitoring problems in high-voltage circuits. The effect will be illustrated with the help of the circuit in figure 6. Such a circuit results when a phase-to-pilot fault occurs. The supply voltage in the circuit is assumed to be 4,160 volts (line-to-line). R_N is the neutral resistor and is sized at 96 ohms to limit the fault current to 25 amp. R_{MC} is the resistor mounted at the machine end to detect pilot-to-ground faults (typically sized at 4 ohms). Thus, during the fault the voltage appearing across pilot-to-ground at the monitor terminals will be approximately 25 X 4 = 100 volts, which can cause monitoring problems.

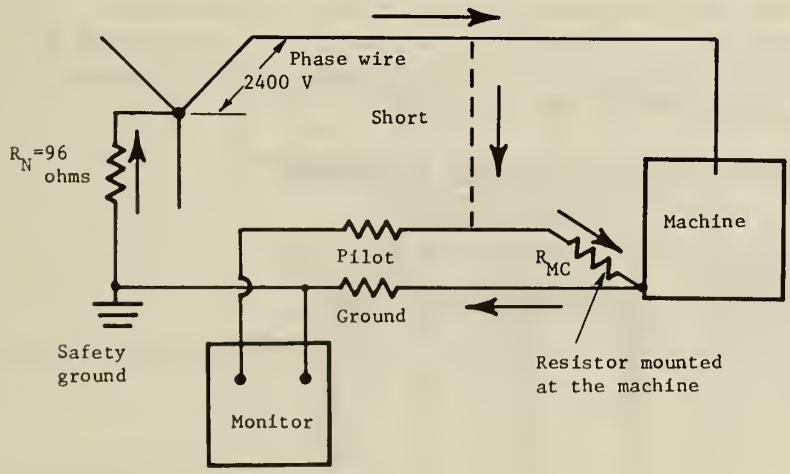


FIGURE 6. - Circuit to illustrate a phase-to-pilot short circuit. Arrows indicate the current flow.

Lightning Transients

Lightning is a major problem in surface coal mine

systems since all the equipment is aboveground and thus directly exposed. The large booms of draglines and shovels seem to be especially susceptible to direct lightning strokes. The huge currents associated with lightning (5-50 kamp), although of short duration (a few microscconds), can give rise to tremendous overvoltages on the system. These high-voltage transients can be transferred to circuits where the monitors are located through various pathways. There have been many instances of monitor failure caused by lightning transients.

Estimation of the severity of the lightning transient problem requires the determination of two aspects of the lightning phenomenon. First, it is necessary to estimate the exposure of the particular system--that is, to calculate the expected number of direct strokes and nearby strokes per year--in order to develop a statistical distribution of current impulses in the system. Second, it is necessary to estimate the magnitude of the voltage transients on the monitor produced by a particular lightning current transient.

Estimation of the distribution of current impulses can be carried out from the physical description of the system. This has been given in detail in reference 1 and will not be repeated here.

The various pathways by which the high voltage produced by lightning can reach the ground wire monitor are--

1. Static wire of incoming overhead line.
2. Phase conductor of incoming overhead line.
3. Dragline or other equipment frames.
4. Primary substation.
5. Breaker box or portable substations.
6. Earth near safety grounded equipment and near the cable itself.

Attempts were made to model each pathway, making a few assumptions. Based on these models, estimates were made for the frequency of occurrence of each path that would cause monitor failure on a 1-year base, with the probability of lightning discharge magnitude shown in table 1.

TABLE 1. - Probability of lightning discharge of particular currents

Current, kiloamperes	P(I) per unit	Current, kiloamperes	P(I) per unit
5	0.1	30	0.05
6	.1	35	.05
7	.1	50	.05
8	.1	60	.01
10	.1	65	.01
12	.1	75	.01
17	.1	80	.01
25	.1	120	.01

One of the pathways (incoming static wire) will be fully analyzed, and the final results from a similar analysis of the other pathways will be presented. The complete details are given in reference 1.

Analysis of Lightning Stroke to Incoming Static Wire

The static wire can be represented by the equivalent circuit in figure 7. At each pole the static wire is connected to ground by bare wire running down the pole with an equivalent impedance Z_r. The surge impedance of the static wire is Z_{gg} as shown.

Lightning strikes the static wire (the strike is assumed to be at midspan) and induces a surge voltage V_g which travels along the static wire toward the substation. At each intersection of the static wire and ground wire, reflection takes place because a change in impedance is encountered by the surge voltage V_g. A portion of V_g is reflected back, and the rest passes through and reaches the next pole. Again reflection takes place, and another portion is reflected back. Likewise, the magnitude of V_g is reduced by a certain amount at each pole and at the last pole. The final voltage V_t that appears on the system ground bed via the last pole ground is the voltage that causes a potential difference between the system ground and the safety ground. Since the two ground beds are relatively far away from each other, the rise in potential of the safety ground is insignificant compared to that of the system ground.

The ground check monitor is monitoring the safety ground wire, which is relatively near zero potential; the monitor is mounted on the frame of the substation. It can be seen that a voltage difference of V_t appears across the monitor frame and the point inside the monitor circuitry upon which the safety ground wire is connected. When this voltage V_t gets over a certain limit, flashover occurs inside the monitor and damages the circuity. This is the basic assumption on the mechanism of monitor failure.

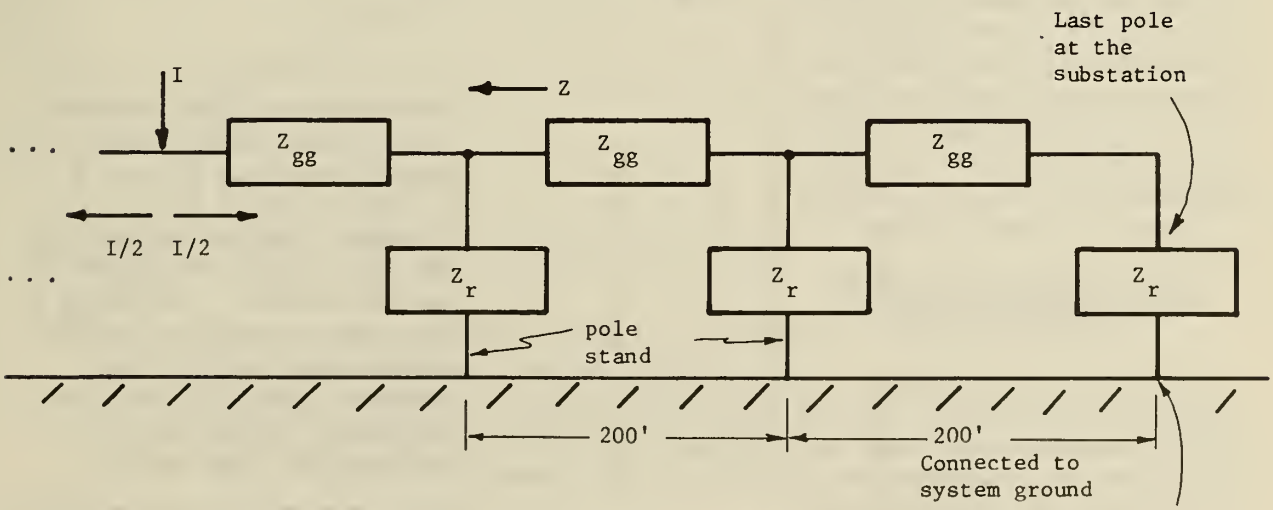


FIGURE 7. - Equivalent circuit for incoming static wire.

To estimate the frequency of occurrence of monitor failure due to this path, a systematic approach is developed. First, a reasonable value for V_t that will cause monitor failure is assigned. Second, for a given magnitude of lightning current, one determines the number of pole sections and hence the distance away from the substation at which the transmitted surge voltage caused by lightning can have a value equal to or greater than V_t. Third, for this particular type of transmission system, one determines the frequency at which this length of the static wire is being struck by that magnitude of lightning current. Fourth, steps 2 and 3 are repeated for the whole spectrum of current magnitude shown in table 1. Finally, all the values are summed to give the resultant frequency of occurrence of this path.

From figure 7

$$V_g = Z_{gg}(I/2), \tag{1}$$

$$Z = Z_{gg} \,||\, Z_r = \frac{Z_{gg} Z_r}{Z_{gg}+Z_r}, \tag{2}$$

and transmission coefficient $T = \frac{2Z}{Z+Z_{gg}}$. (3)

At the first pole intersection $V_{t1} = T\, V_g$, (4)

at the next pole $V_{t2} = T\, V_{t1}$,

and so on to V_{tn}.

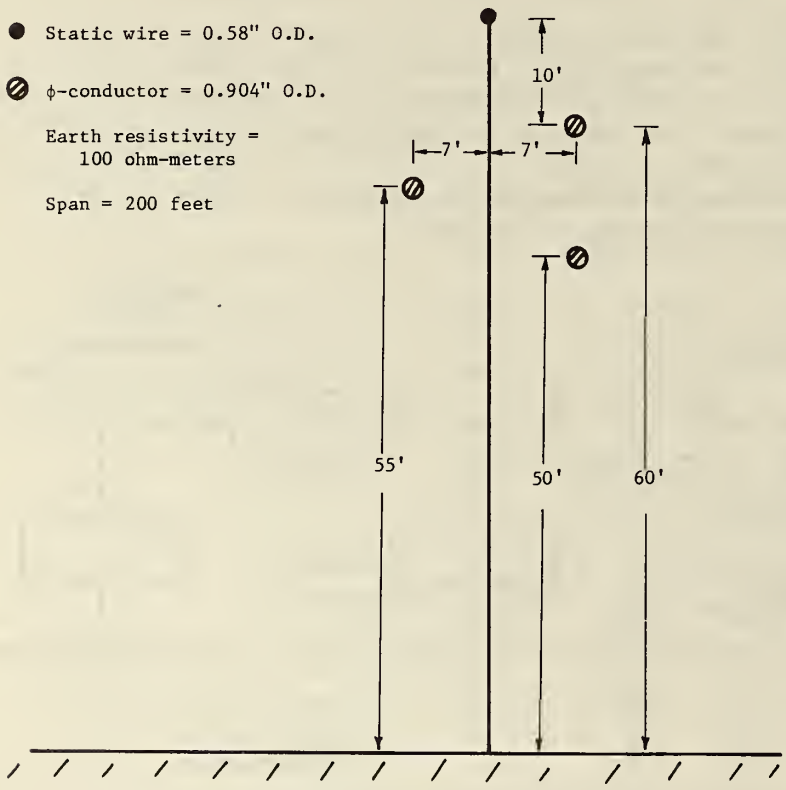


FIGURE 8. - Configuration of incoming line.

At the last pole,

the transmission coefficient

$$T_L = \frac{2\, Z_r}{Z_r+Z_{gg}}, \tag{5}$$

and the transmitted voltage,

$$V_t = T_L\, V_{tn}. \tag{6}$$

The configuration and dimensions of the transmission system under study are approximated in figure 8. A typical value for Z_r is 20 ohms. The value for Z_{gg} was calculated and found to be 533.34 ohms. Assuming a destructive voltage V_t of 1,000 volts and an isokeraunic level of 50,[4] the frequency of occurrence per year by this path is

[4]Number of thunderstorm days per year.

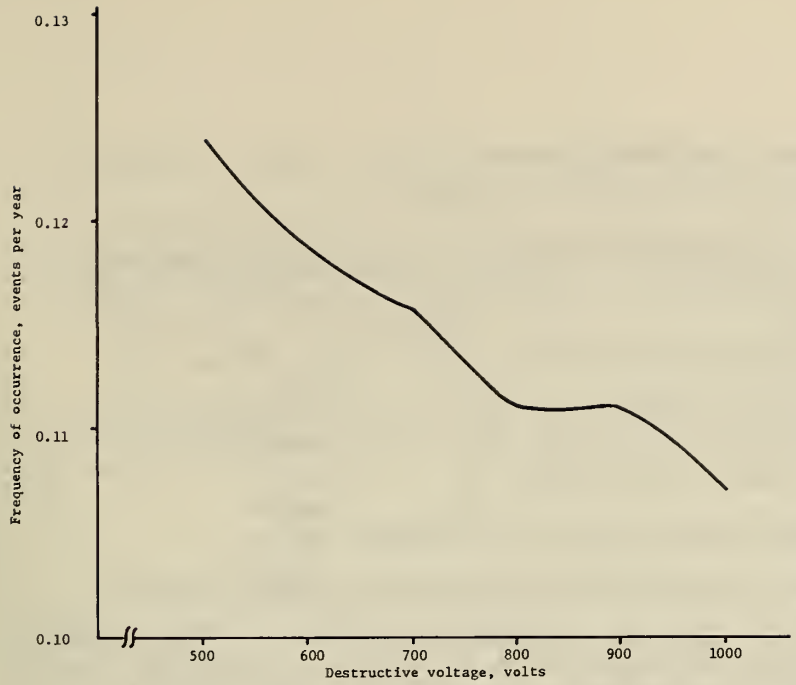


FIGURE 9. - Frequency of occurrence of domage to monitor for lightning strikes to the stotic wire os o function of the destructive voltoge. Colculotions ore bosed on o line footing impedonce of 20 ohms.

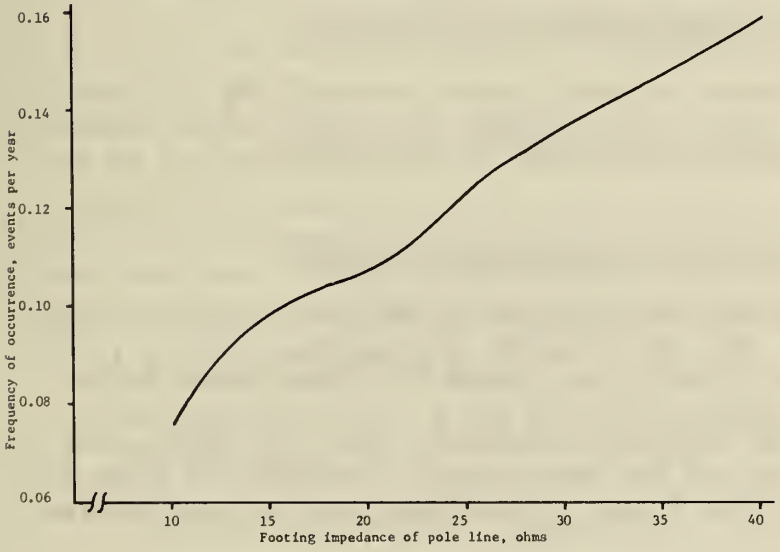


FIGURE 10. - Frequency of occurrence of domage to monitor for lightning strokes to the stotic wire os o function of footing impedance of the pole line. Colculotions ore bosed on o destructive voltoge of 1,000 volts.

calculated to be 0.107, or once every 9.3 years. That is, one monitor will be destroyed by lightning every 9.3 years by this pathway.

A series of computations were made by varying the destructive voltage V_t from 1,000 volts to 500 volts, and the result is plotted in figure 9. The curve shows a steady rise in the frequency of occurrence as V_t decreases.

Next, computations are made by varying the footing impedance of each pole; the result is shown in figure 10. Notice that the change in frequency is quite steady when the footing impedance is about 15 ohms. There is a rather steep drop in frequency below 15 ohms.

One point must be mentioned concerning the distance away from the substation. The calculations indicate that even for the highest discharge current of 120 kamp, the distance is less than four pole sections. Farther away from that section, lightning has no effect at all, for most of the current will be directed to ground along the way.

Summary of Results From Other Pathways

Table 2 summarizes the results obtained by a similar analysis of other pathways. It gives the frequency of occurrence by each pathway that will result in monitor failure. When all the

pathways are taken into account (assuming 5 miles of pole line), the final result is summed up to be 1.97, or once every 6 months.

TABLE 2. - Frequency of occurrence of destructive voltage, by pathway

Pathway	Frequency of occurrence per year
a. Incoming static wire.....	0.107
b. Incoming phase conductor.....	.341/mile
c. Dragline.....	.09892
d. Inline breaker and portable substation..	.053
e. Primary substation.....	.00565
f. Earth near equipment.....	.00178
g. Earth near cable.....	.001577

The results in table 2 show that the incoming phase wire has the highest probability, followed by the path through the static wire and dragline. Pathways d, e, f, and g are of less significance. Protection efforts can be focused mainly on pathways a, b, c, and d.

MONITOR DESIGN REQUIREMENTS AND CONSIDERATION

Based on the analysis already presented, the following design requirements are suggested for high-voltage ground wire monitors.

Immunity to 60-Hz Voltages and Currents

The monitors should be immune to 60-Hz induced currents (up to 5 amp) flowing in the ground wire. Also, 60-Hz voltages (up to 100 volts) appearing between pilot and ground terminals should have no undesirable effect on the performance.

Ability To Monitor Long Lengths of Cable

As already seen, most of the cable lengths encountered in surface monitors are a few thousand feet. For these lengths and monitors working in the audio frequency range, the cable has to be treated as a distributed rather than a lumped element. This can give rise to grave monitoring problems. Preliminary studies done at West Virginia University show that these transmission line effects are pronounced for cable lengths in excess of 5,000 feet and monitoring frequencies of over 5 kHz. DC monitors face no such problem.

Immunity to Parallel Paths

Most surface mining equipment frames are in good earth contact and can present low resistances which are sometimes hard for monitors to detect. However, it is desirable for the monitors to have the ability to detect ground wire failure in spite of parallel paths.

Pilot-to-Ground Short Circuit

The monitor should have the ability to detect a pilot-to-ground short circuit. Usually, this can be accomplished by mounting a resistor or a filter at the machine between the pilot and the ground wire.

Large Temperature Variations

Owing to the nature of their application, the monitors should be able to operate efficiently under large temperature variations. The suggested values are -25° to 70° C (-15° to 160° F).

Immunity to High-Voltage Transients

As shown already, large voltage transients can be produced at the monitor terminals due to lightning strokes. All the elements within the monitor that are connected directly to the input terminals (supply transformers, rectifiers, relays, etc.) should have adequate basic impulse levels. Also surge protection should be provided between the pilot and ground terminals at the monitor and also between the ground and the case.

Flags To Indicate Nature of Tripping

There can be several abnormal conditions within the system for which the monitor can trip. It is highly desirable that the monitor be capable of identifying the nature of fault (ground wire open, pilot-to-ground short, etc.). It is an added advantage if a rough indication of the location of the fault is also given.

COMMENTS ON COMMERCIALLY AVAILABLE MONITORS

Some of the commercially available high-voltage ground wire monitors were tested in the laboratory to evaluate their performance under simulated abnomal system conditions. However, since the tests are being conducted in a laboratory environment, the actual performance in the field might differ substantially.

The available monitors on which initial tests have been carried out are--

1. Atkinson Armature Works Co. type AAW7700 Omser (hereafter referred to as Atkinson).
2. Central Electrical Co. type RJL-300 (hereafter referred to as CEMSCO).
3. General Electric Co. type MEO-DP-3AM.
4. FEMCO Ground Sentinel II.
5. AMF Potter-Brumfield.

The operating principle of each monitor and the performance obtained are discussed below.

Atkinson Monitor

The connection diagram for the Atkinson monitor is given in figure 11. Basically, it is a dc monitor which uses a bridge circuit with a voltage comparator to measure resistance. A second comparator is used to detect a "too low" resistance representing a pilot-to-ground fault. In other words, the two comparators form a window detector. The monitor is also equipped with pilot lights to indicate whether the tripping was due to pilot-to-ground resistance being too low or too high and uses a 4-ohm resistor connected between pilot and the ground on the machine frame to detect pilot-to-ground short circuits.

The monitor was very sensitive to changes in the impedance of the ground and pilot wires and tripped for all abnormal conditions. It also tripped for pilot-to-ground shorts. Stray ac currents in the ground wire (up to 2.5 amp) and induced voltages in the pilot-to-ground circuit (around 20 volts) seemingly had no ill effect on the performance. The monitor worked well when the supply voltage was increased by 10 pct of the nominal, but poor performance was obtained when the voltage was decreased by 12 pct.

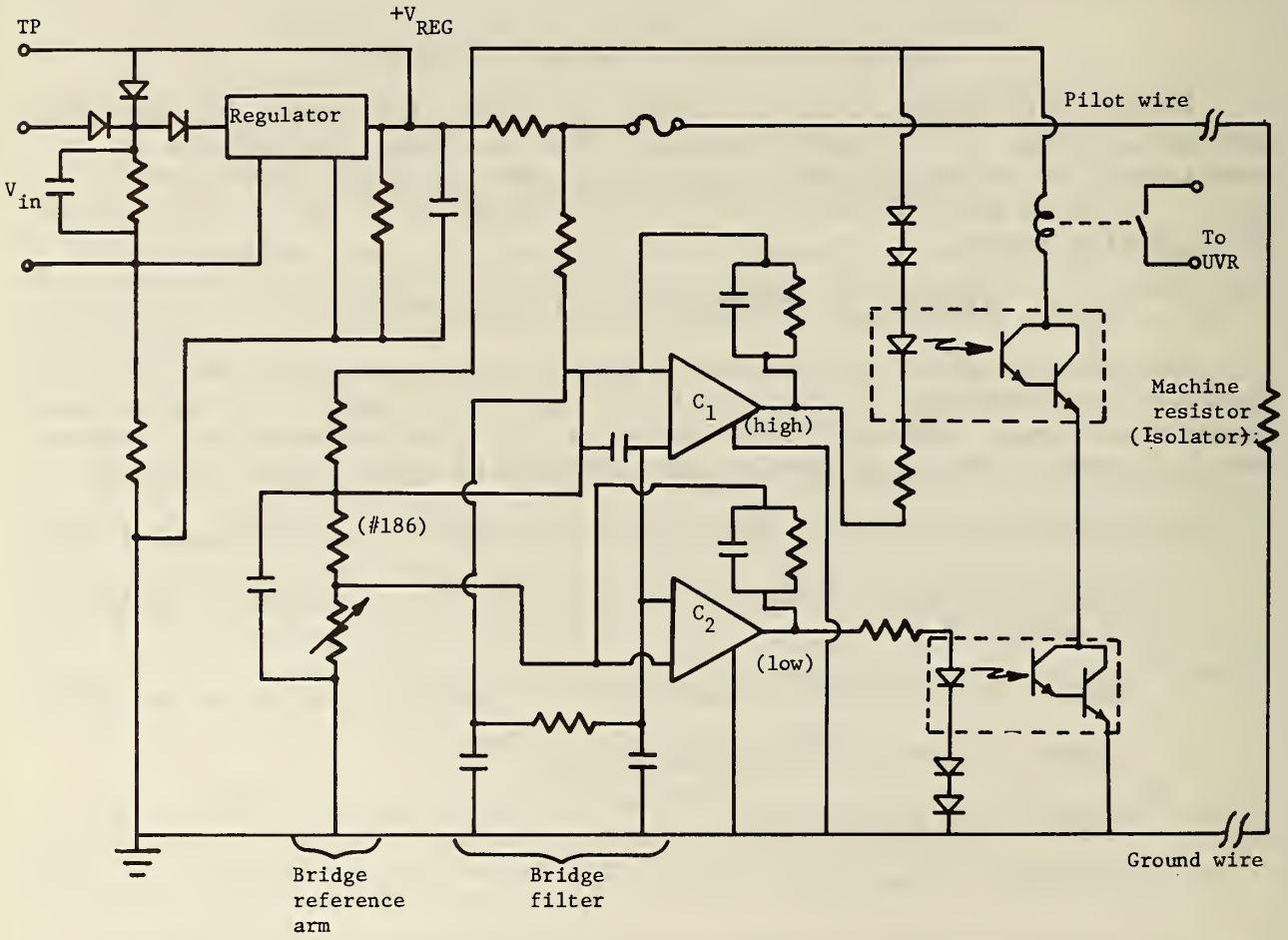


FIGURE 11. - Circuit diagram of Atkinson monitor.

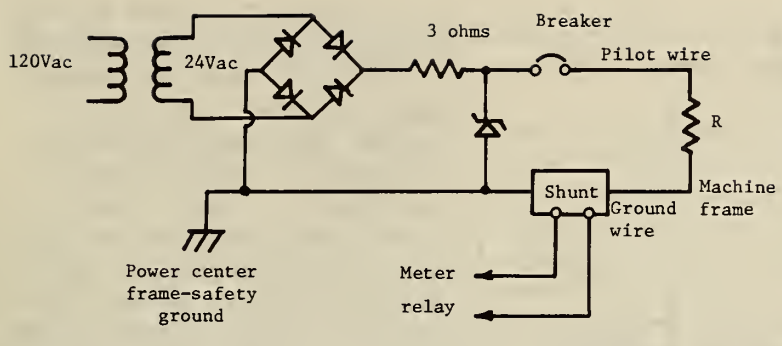


FIGURE 12. - Basic circuit diagram of CEMSCO monitor.

The monitor worked well when subjected to a temperature of 65° C in an environmental chamber. However, when it was left at 80° C for some time, the main power supply rectifier failed. The monitor also does not have the capability to detect parallel paths.

CEMSCO Monitor

The connection diagram for the CEMSCO unit is given in figure 12. In this monitoring technique a dc current (≃0.9 amp) is circulated in the pilot-to-ground circuit. A small dc voltage (≃2 mv), which is developed across a groundwire shunt, is fed to a meter relay. The meter relay senses any decrease in the pickup voltage and trips in case the voltage is less than the set point. This will happen for any substantial increase in resistance of the pilot-to-ground circuit. There is a small circuit breaker in series with the pilot wire. This breaker is equipped with a thermal trip, which is set for a time delay of approximately 10 to 15 seconds for a current of 2 amp. If there is a pilot-to-ground short circuit, the current will increase, thereby tripping the circuit breaker and opening the pilot-to-ground circuit. This in turn will operate the monitor. The monitor also uses a 25-ohm adjustable resistor connected between the pilot and ground at the machine frame. The dc voltage in the monitoring loop is around 24 volts.

The monitor satisfactorily tripped for changes in the ground and pilot wire resistances under normal circumstances. However, if the monitor was originally set when a low parallel path was present and subsequently the parallel path was removed, the monitor failed to trip even when the ground wire resistance was increased to 10 ohms. It also did not perform well when induced voltages of the order of 20 volts were present in the pilot-to-ground circuit. The unit performed well when the supply voltage was increased by 10 pct of the nominal. However, it seems to be sensitive to dips in supply voltage and showed uncertain performance for voltage dips in excess of 10 pct. The monitor seems to be built quite ruggedly and showed no undesirable effects even when operated at 80° C for several hours.

General Electric Monitor

The GE monitor is basically a dc series loop-type monitor using a meter relay for sensing current. The monitoring current is approximately 2.5 amp. The basic circuit is given in figure 13. The potentiometer is used to adjust the current in the loop. The monitor also uses a 3-ohm external resistor connected between ground and the pilot at the machine end. The output is protected by a surge suppressor and a capacitor connected across pilot to ground.

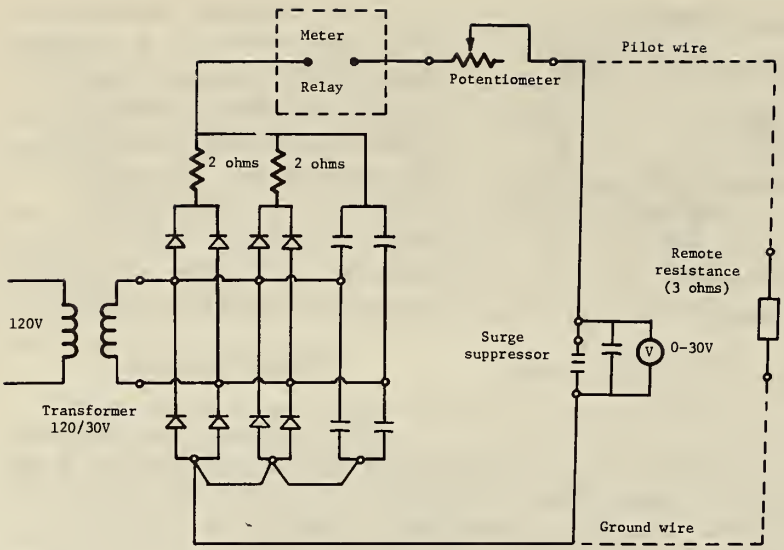


FIGURE 13. - Basic connection diagram of the GE monitor.

The monitor was set for approximately 6,000 feet of 4/0 cable. This is equivalent to about 0.5-ohm of ground wire resistance and 4.0 ohms of pilot wire resistance. The current sensitivity was set at ±0.5 amp, as suggested by the manufacturer to avoid nuisance tripping. During testing it was found that the correct adjustment of the potentiometer was very important for sensitive monitor performance. In fact, for a high value of resistance (around 7 ohms) the monitor failed to trip for a pilot-to-ground short circuit. For this test sequence the potentiometer was adjusted around 2 ohms, which gave better sensitivity.

The monitor was also quite sensitive to changes in the ground and pilot wire resistances and tripped under pilot-to-ground short circuit. Stray ac currents flowing in the ground wire (up to 2.5 amp) did not impair the performance. The monitor does not have the ability to detect parallel paths. It also seems quite sensitive to dips in the supply voltage. The monitor did not perform satisfactorily for dips in excess of 10 pct. The monitor was left in an environmental chamber at 65° C and showed no undesirable effects. However, when the temperature was increased to 80° C, the reset knob of the monitor failed to function.

AMF Potter-Brumfield Monitor

The connection diagram for the AMF monitor is given in figure 14.

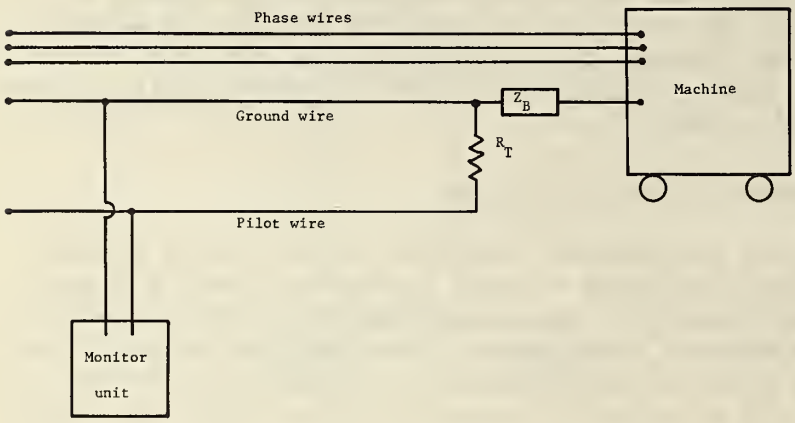


FIGURE 14. - Connection diagram for the AMF monitor.

The monitor sends out a 1,000-Hz sine wave into the monitoring loop. The monitor has ratio and phase detectors which constantly measure the magnitude and phase of the impedance seen by the monitor. The monitor has a complex logic built into it by which it can both differentiate between different kinds of faults and give a fair idea of the approximate location of a fault. The circuit also seems to

have some redundancy built into it. The blocking impedance Z_B is made up of the same size of wire as the ground wire and prevents the signal from going through the machine frame into the ground.

According to the manufacturer, each monitor is capable of monitoring only one section of a feeder cable. The printed circuit cards containing the monitoring circuitry are fabricated for different cable lengths (to be specified by the user) and hence need no adjustment in the field. This has both advantages and disadvantages. Since the monitor requires minimum adjustment in the field, it is likely to be free from installation errors made by unskilled personnel not familiar with monitor operation. However, a feeder cable feeding portable equipment is made up of many sections; hence just to monitor one complete length of the cable, one would require many monitors.

The blocking impedance mounted at the machine is used to prevent parallel paths. However, this impedance itself is not monitored. If a break or a loose connection should occur within this impedance, one may lose the ground at the machine, but the monitor will still show a safe condition. However, the probability of such an occurrence is remote.

The monitor showed excellent performance in detecting resistance changes in the pilot and the ground wires. It also tripped satisfactorily on pilot-to-ground short circuit. Stray ac and dc on the ground wire (up to 2.5 amp) seemingly did not affect the performance characteristics. The monitor seemed to be immune to supply voltage variations. Satisfactory performance was obtained for supply voltage variations of -40 to +15 pct of the nominal.

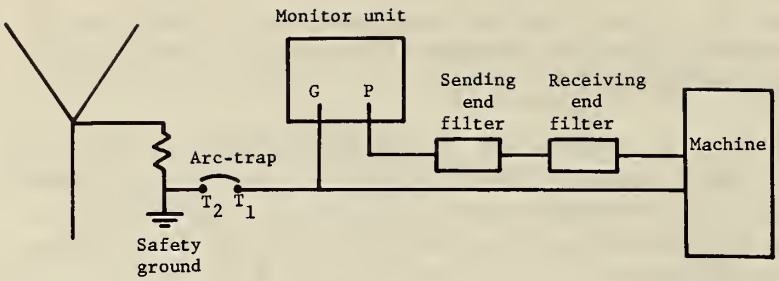
The monitor is equipped with flags to indicate the type of fault--a ground wire break, pilot-to-ground short circuit, etc. According to the manufacturer, a combination of these flags was to indicate whether the fault occurred in the cable close to the monitor unit or near the end of the cable. However, this facility does not function properly.

The monitor tripped on small increases in the line inductance. There is a possibility of a change in the cable inductance occurring due to spooling or unspooling. However, since no experimental data are available in this respect, no conclusions can be derived.

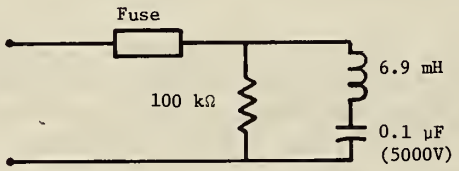
FEMCO Ground Sentinel II Monitor

The connection diagram for the FEMCO monitor is shown in figure 15. The monitoring signal is approximately 4 kHz, and the circuit has to be turned in the field depending on the length of the cable being monitored. Also the sensitivity of the monitor to detect resistance changes has to be adjusted in the field. Hence it is imperative that the installation of the monitor in the field be carried out by experts who are quite familiar with its operation.

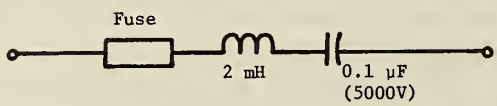
The monitor shows satisfactory performance in detecting changes in the resistance of pilot and ground wires and pilot-to-ground short circuit. It showed immunity to stray ac and dc (around 2.5 amp), and the tripping point did not change considerably. Variations in the supply voltage seemingly had



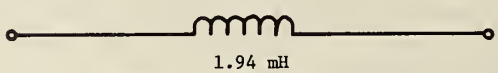
Connection diagram for FEMCO monitor



Receiving-end filter



Sending-end filter



Arc-trap

FIGURE 15. - FEMCO high-voltage ground wire monitor. G = ground wire terminal; P = pilot wire terminal; T_1 = terminal 1 of arc-trap; T_2 = terminal 2 of arc-trap.

no effect on the performance characteristics. Excellent performance was obtained when the supply voltage was varied from -40 to +15 pct of the nominal value.

The arc trap in series with ground wire eliminates parallel paths. However, the arc trap by itself is not monitored, and if any break in connection occurs, the monitor fails to indicate an unsafe condition.

There are two LED's to indicate monitor tripping. One of them goes off when the abnormal condition that caused the monitor to trip is removed. The other stays on till the monitor is reset. However, there is no indication as to whether the triping was caused by an open ground, a pilot-to-ground short, etc.

When the line inductance was increased by 1 mh (to simulate a long cable), a noticeable decrease in the sensitivity of the monitor was observed. In some instances the LED's indicating the tripping condition operating before the output relay had operated. This indicated that the monitor may have problems in monitoring very long lengths of cable. Also at longer lengths (and high frequencies such as the one employed by this monitor) the cable can no longer be modeled as a lumped element and transmission line effects are to be taken into account. However, this is a subject of future investigation by West Virginia University, and any inferences at this stage may be rather premature.

CONCLUSIONS

The problems encountered by ground wire monitors in surface coal mine applications have been adequately described. Based on these, some design requirements for monitors are suggested. Results have been presented from laboratory testing of some of the commercially available monitors. This testing program is continuing to evaluate the ability of the monitors to withstand high-voltage transients generated by lightning.

REFERENCE

1. Cooley, W. L. Mine Grounding Systems: Evaluation of Ground Beds and Ground-Bed Monitors and Evaluation of Modular Ground-Wire Monitor (1975-76 Annual Report, U.S. Bureau of Mines Grant G0144138). BuMines Open File Rept. 122-77, May 1977, 349 pp.; available for consultation at the Bureau of Mines facilities in Denver, Colo., Twin Cities, Minn., Bruceton and Pittsburgh, Pa., and Spokane, Wash.; at the U.S. Department of Energy facilities at Carbondale, Ill., and Morgantown W. Va.; at the National Library of Natural Resources, U.S. Department of the Interior, Washington, D.C.; and from the National Technical Information Service, Springfield, Va., PB 270 900/AS.

GROUND BED DESIGN AND MEASUREMENT

by

Herman W. Hill, Jr.,[1] and Wils L. Cooley[2]

ABSTRACT

The electrical behavior of ground beds is often quite different from what would be expected based on experience with electric circuits. An explanation for this unique behavior is given, through means of an analogy, which should promote intuitive understanding of ground beds. The nonmathematical development of the text is complemented by an extensive appendix which describes the details of ground bed calculations. This work was supported by U.S. Bureau of Mines contract G0144138.

INTRODUCTION

The design and resistance measurement of ground beds are subjects that have suffered greatly from misconceptions. Although the topics may appear elementary, their subtleties have led even experienced engineers astray and resulted in inefficient or improper systems which go unrecognized as such. Also, ground systems may be mishandled because the people who install them are not well trained in grounding. Often a good mixture of common sense, intuition, and practical experience has brought these persons success as mine mechanics or engineers, but many of the properties of grounding networks are contrary to intuition, making it very hard for those without a theoretical background to understand the system. This paper is designed to provide a deeper theoretical understanding for those who are now intuitively relating to the system. It presents an analogy that allows subtle aspects of ground beds to be understood without resorting to mathematics.

THE RUBBER SHEET ANALOGY

Experience with electrical circuits is not particularly helpful in ground bed design and measurement. In fact, such experience can be a hindrance if it generates unfounded expectations that ground beds behave as ordinary resistors. Two examples of such expectations follow:

1. The total resistance of two identical rods tied together is half the resistance of either rod. (Not true.)

2. The resistance of a ground bed can be measured with an ohmmeter. (Not true.)

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If familiarity with circuits is a poor guide, something else must be found to replace it. For some engineers, the mathematical theory alone will suffice, but even these persons will benefit from an alternate method of viewing ground beds. Several methods exist; the one developed here is an analogy, specifically, the analogy of an elastic sheet. That is, the rise in potential of a ground bed and nearby earth can be thought of as the distortion of a rubber membrane due to a weight of force applied through small plates glued to the sheet. The analogy perhaps can be best detailed by describing the factors that ground beds carrying current and elastic sheets being stretched have in common.

The potential to which a ground bed (and the earth near it) will rise, due to a current which the bed carries, is proportional to that current. The potential is directly proportional to the resistivity of the earth in which the bed is built and inversely proportional to the size of the electrode(s). If the bed is built from more than one rod (or other electrode), the potential is lower if the electrodes are mutually distant from each other than if they are close. The ratio of the potential (with respect to a point very far away) to the current is called the resistance of the ground bed.

The deflection sustained by a rubber sheet, due to a weight fastened to it, is proportional to that weight. This distance that the sheet is pulled down is directly proportional to the elasticity of the sheet to which it is fastened and inversely proportional to the size of the contact plate on the sheet used to fasten the weight. If the weight is fastened in more than one place, the deflection will be less if the fastening points are mutually distant from each other than if they are close. The ratio of the deflection (measured with respect to the edge of the sheet) to the applied weight (force) is called the compliance of the contact plate(s).

It seems inaccurate to refer to this compliance as a property of the contact plates, because it actually depends equally on the elasticity of the entire sheet. The widespread custom of referring to the resistance as a property of the ground bed because it depends on the earth resistivity around the bed is similarly misleading.

EARTH RESISTIVITY

In terms of the rubber sheet analogy, resistivity is the electrical "elasticity" of the earth; that is, the amount of deflection (potential) for a given weight (current) that a section of the earth undergoes. One of the greatest difficulties with ground bed design and measurement is that this earth resistivity varies enormously from point to point along the surface. (A very accurate rubber sheet model of the earth would be a sort of patchwork quilt made of irregular patches--some of very thin, soft rubber, others of rigid material, and the rest with intermediate elasticity.) The resistivity of the earth also changes with depth; the rubber sheet model cannot show this very well, being essentially a two-dimensional analogy.

Resistivity near the ground bed site affects the resistance of the bed more than distant resistivity does because the current spreads out in all

directions as it flows away from the bed; thus, more current flows through a cubic foot of earth near the bed than through a cubic foot far away. Therefore, to build a low-resistance ground bed, it is important to know the earth resistivity at the ground bed site for two reasons: (1) The size of the bed cannot be calculated without this resistivity, and (2) the best site (lowest resistivity) for the ground bed cannot be found without it.

MEASUREMENT OF EARTH RESISTIVITY

All electrical measurements of the earth are subject to the basic limitations of electrical circuits. The most-often encountered problems are that a current that enters the ground from a current source at one point must leave the earth at a second point to return to the source in a complete external circuit, and that only voltage differences, not absolute potentials, can be measured. In terms of the analogy, the first limitation means that if a force is applied to the sheet at one point, pulling down on the sheet, an equal force must be applied at another point, pulling up. The second constraint limits deflection (altitude) measurements to the differences in height of relatively nearby sections of the sheet and forbids measuring the "absolute" deflection of the sheet with respect to the frame over which the sheet is stretched.

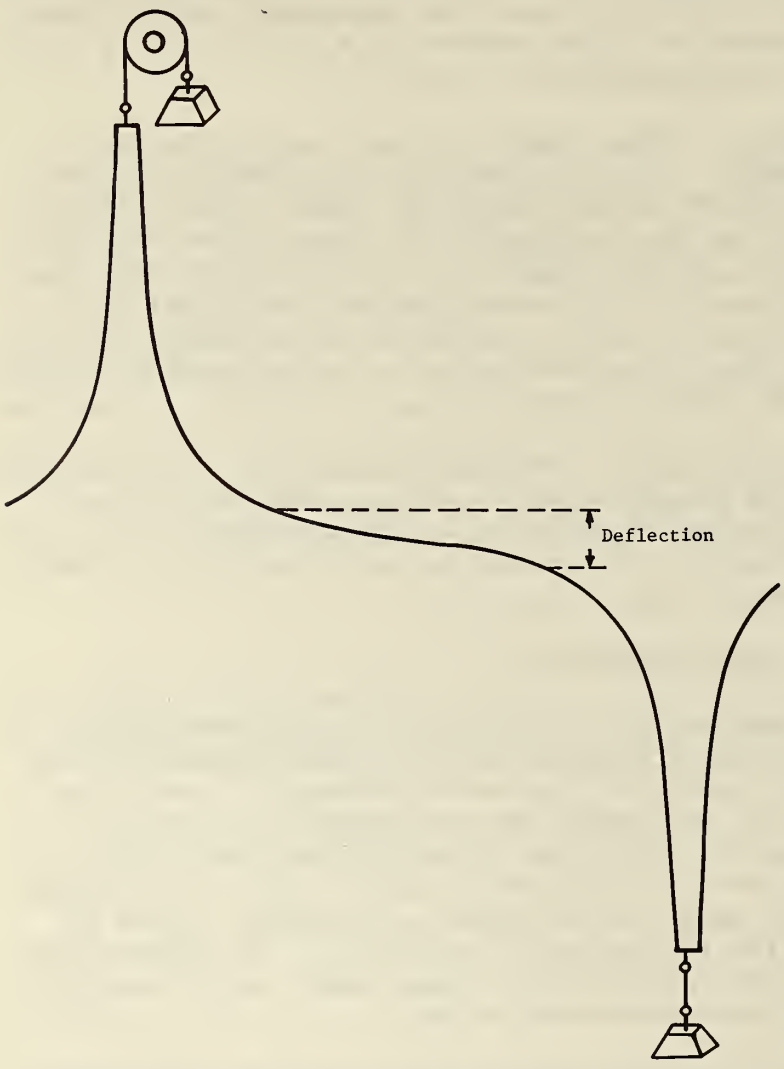

FIGURE 1. - Deflection of elastic sheet by equal and opposite forces.

Consider the contour of the elastic sheet, along a path between the points where two equal and opposite forces are attached, as in figure 1. If the width of the contact plates is much smaller than the distance between the plates, the curvature of the sheet, particularly near the midpoint of the path, will not be affected by the plates. The difference in height between any two points along this path is proportional to the elasticity of the sheet and to the applied force. Most resistivity methods are based on an analogous technique, that of passing a

current between two points in the earth and measuring the voltage between two other points along the line connecting the current application points. In the Wenner array, the voltage is measured between two points that are located at one-third and two-thirds the distance from one current electrode to the other. In this case, the resistivity is given by

$$\text{Resistivity} = \frac{\text{(measured voltage)}}{\text{(applied current)}} \times \text{(spacing)} \times (2.094).$$

If the spacing from one current electrode to the other is measured in feet, resistivity will be in ohm-feet; if the spacing is in meters, resistivity will be in ohm-meters, etc.

Th Schlumberger array uses a very small spacing between the two points where the voltage is measured. If the distance between the two voltage electrodes is called Y and is much less than the current-electrode spacing, then

$$\text{Resistivity} = \frac{\text{(measured voltage)}}{\text{(applied current)}} \times \frac{\text{(spacing squared)}}{Y} \times (12.57).$$

The Schlumberger array is used primarily for determining voltage gradients (the slopes of potential hills).

TYPES OF RESISTIVITY MEASUREMENTS

In general, the electrodes used to measure resistivity will span areas of different resistivity. The measured resistivity will then be an average of the different areas. By placing the current and voltage electrodes farther and farther apart, the resistivity of a larger and larger volume of earth is averaged. To determine the variation in resistivity over a tract of land, the Wenner array is used, with short spacings, and all four electrodes are moved together to various measurement locations over the tract. This technique is known as resistivity mapping. (If the electrodes are used at very small spacings, the shape of the electrodes used affects the measurement and should be taken into account.) Another technique, known as resistivity sounding, provides information about how the resistivity varies with depth. The technique consists in taking resistivity measurements with the Wenner array at a series of different spacings, keeping the array centered always over the same point.

RESISTANCE OF EARTH ELECTRODES

The resistance of a borehole casing, rod, or other earth electrode can either be calculated using measured earth resistivity, or measured directly. In practice, both methods are necessary. In designing a ground bed, resistances must be calculated to determine the number of electrodes needed and the required interelectrode spacings. The resistance of the constructed bed should be measured to confirm the design and also later, periodically, to check for deterioration of the bed. Formulae for calculating the resistance of various electrodes are given in an appendix to this paper; here the methods of measuring resistance are discussed.

Resistance Measurement of a Single Electrode

In making a resistance measurement on a single electrode, the potential of the electrode (with respect to a faraway point) must be found. "Faraway," in this context, means distant enough to be at the bottom of the potential hill of the electrode. As a practical matter, the potential hill extends so far that this voltage can never be measured directly. In addition, just as in resistivity measurements, a return path for the electrode current must be provided. This requires another electrode, which further complicates the picture. In terms of the rubber-sheet analogy, if the polarity of the current applied to the ground bed is positive, creating a potential hill, the return electrode creates a nearby valley. This valley lowers the height of the rubber sheet for great distances around. In particular, the height of the potential hill of the ground bed is reduced somewhat by this valley. (The depth of the valley is also reduced by the hill.)

The problem of resistance measurements of a ground bed reduces to the task of finding the height of a potential hill created by a (known) current, taking into account the effect of the current return electrode. An auxiliary electrode must be located such that the voltage measured between it and the ground bed corresponds to the height of the potential hill of the ground bed (with all effects of the current-return electrode removed). For ground beds that are small compared to the distance to the current electrode), this location is easily calculated. For larger beds the location is more difficult to determine.

The potential electrode is commonly located on a straight line between the ground bed and the current-return electrode. However, as long as the potential-electrode coordinates correspond to the correct electrical "height" (potential), the resistance measurement will be accurate. The locus of points (isopotential line) that corresponds to all possible locations of the potential electrode is a rough oval surrounding the current electrode. There is no electrical reason for preferring any one of these points over the rest; by definition, they give the same voltage and therefore the same resistance. Traditionally, the point chosen has been the one on a straight line between the ground bed and the current-return electrode, merely to simplify the measurement procedure. There are two major practical difficulties with this choice. First of all, this is the closest of all possible potential-electrode locations to the ground bed. Now, the exact shape of the potential hill of a practical ground bed is difficult to predict; in fact, the certainty with which the electrical behavior can be calculated increases with distance away from the ground bed. This potential-electrode location is therefore the worst possible choice from the standpoint of exactly knowing the electrical behavior of the bed. The distance to this potential-electrode location is measured along a line which goes directly down the steepest slope of the potential hill. Any errors made in placement of the potential electrode will lead to larger voltage errors than would an error in placement along a line of more gentle slope.

An alternative to the conventional choice for locating the potential electrode is to place it at the same distance from the center of the ground bed as the current-return electrode, such that the distance between the two electrodes is half the distance of either one to the ground bed (fig. 2). While this positioning is slightly more difficult to construct, it has the advantage of having the potential electrode as far from the ground bed as possible. (It is as far as possible from the ground bed because it is located as far from the ground bed as the current-return electrode, which is always located as far from the bed as possible.) The resistance of a ground bed can be measured more accurately with this potential-electrode location because the electrical behavior of the ground bed can be better predicted at this greater distance.

In addition, because the line from the center of the ground bed to the potential electrode crosses the curve of potential-electrode locations at a small angle, the measurement is less susceptible to experimental errors in location than is the measurement with the conventional location of the potential electrode. This method of measuring ground bed resistance is recommended for measuring the resistance of all but a few ground beds for which special methods have been developed. These beds are listed in the appendix.

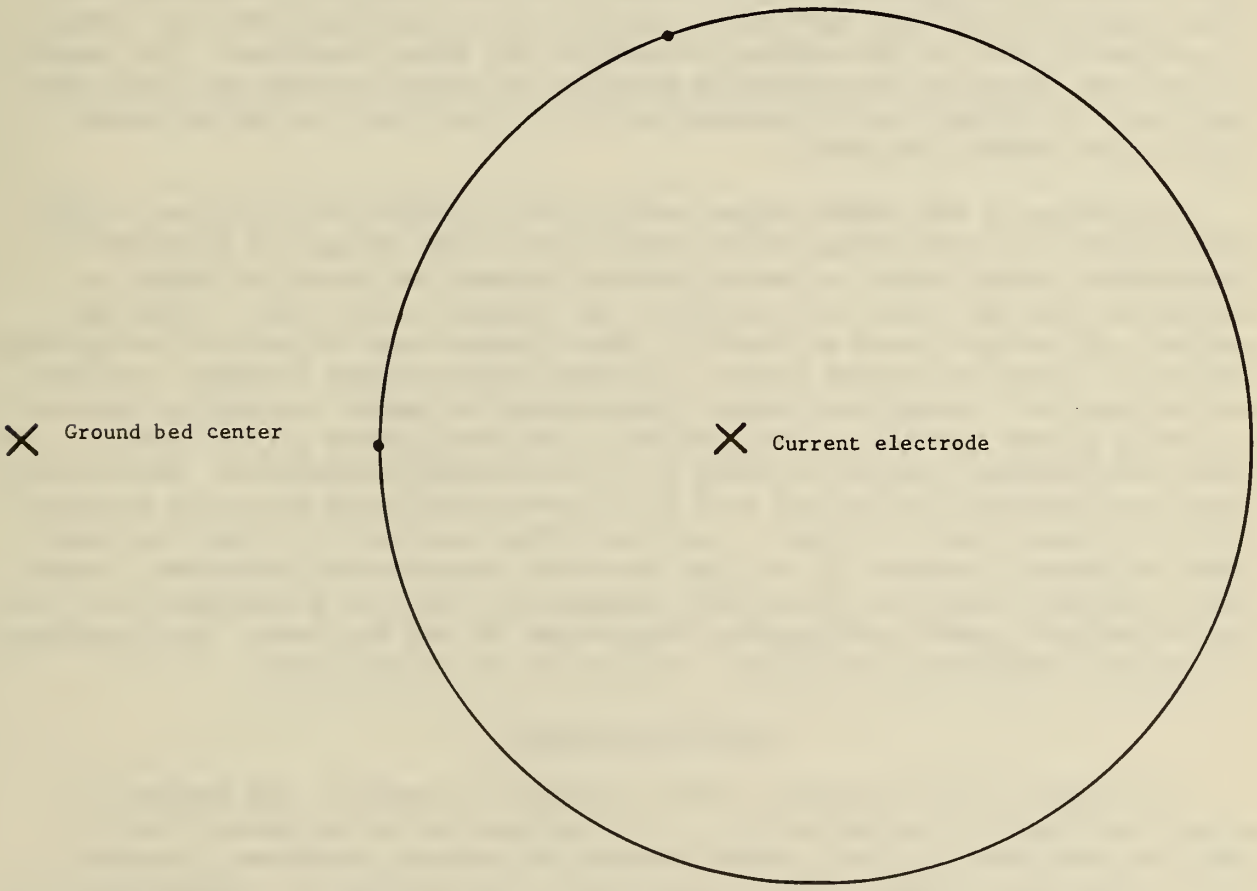

FIGURE 2. - Alternate potential-electrode locations.

Resistance of Multiple Electrodes

The way in which current is distributed among the constituent electrodes of a multiple-electrode bed can be understood through the rubber sheet analogy. Imagine that three weights are to be hung from the sheet in a straight line so that the deflection of the sheet at each of the three attachment points is the same. To keep the problem simple, imagine that each of the small plates on the rubber sheet has the same area. If weights are attached to the first plate in the line so that the sheet sags by the specified amount, and then weights are attached to the second plate, the first plate will end up lower than it should owing to the weights attached to the second plate. To make both plates sag by just the required amount, both plates much have the same weights attached to them. If the plates are very far apart, the correct weight attached to each one will be almost as much as that attached to the first plate before the second carried any weight at all. The closer they are together, the less weight it takes to pull both plates down the specified amount, because each plate sags owing to the weight it carries as well as the weight carried by the other plate.

The analogy to two-conductor ground beds should be obvious: each electrode carries less current than it would if it were the only electrode at a given potential, because each rises (or falls) in potential with the current it carries as well as the current carried by the other electrode. The resistance of two identical electrodes in parallel is therefore more than half the resistance of either one; it approaches the one-half value with very great separations between the beds.

Returning to the rubber sheet analogy, when weights are attached to the third plate, the deflections of the first and second plates are disturbed. Because the second plate is located midway between the first and third, it sags more than the first plate owing to the weight on the third. When the weights are redistributed so that all three plates have the correct deflection, the outer (first and third) plates will have equal weights attached, and the second plate will carry less weight than either of these. As before, none of the three plates carries as much weight as the first plate carried when it alone had weights attached to bring it to the correct deflection. This points out a characteristic of ground beds that is very difficult to accept from an electric-circuit point of view: two electrodes that have the same resistance carry different currents if they are placed in nonidentical positions. When three identical rods are driven into homogeneous earth in a straight line, the middle rod will carry less current than either of the end rods. This phenomenon greatly complicates resistance calculation of large arrays.

Mutual Resistance

To account for the effect of one electrode on another, the concept of mutual resistance is quite useful. It is defined as the potential rise of one electrode due to a unit current carried by another electrode. Because a mutual resistance exists between every pair of electrodes in a ground bed, the calculations rapidly become very complicated, as the number of electrodes increases. Details of the calculations are given in the appendix.

CONCLUSION

An intuitive "feel" for ground-bed behavior cannot be developed through experience with electrical circuits; in fact, such experience may be a hindrance. The rubber sheet analogy, presented here, does provide a physical picture of the relevant electrical phenomena; this picture is qualitatively accurate for most ground bed considerations except potention variation with depth. As demonstrated here, this analogy allows for understanding of subtle aspects of ground beds, such as mutual resistance effects and problems with resistance measurement, without resorting to mathematics. Relevant design equations, as well as derivation of the analogy, were placed in an appendix to provide quantitative help to design personnel without detracting from the nonmathematical picture presented in the text.

APPENDIX

Earth resistivity should be measured using the Wenner array (see text) with an electrode spacing on the order of the ground bed dimensions. The average resistivity thus measured should be used in the formulas of table A-1. Where the earth resistivity is known to vary with depth, and reliable data can be obtained for layer thickness and resistivity (either from borehole resistance measurement or curve matching), the formulae for borehole-casing resistance in layered earth can be used. One method of determining layer resistivities is given in Orellana and Mooney.[1]

Use of the Resistance Tables

The general process of calculating the resistance of a particular configuration of electrodes consists of--

1. Numbering the electrodes 1 through N.

2. Calculating the elements of the symmetric N by N resistance matrix, where R_{ij} is the mutual resistance between electrode i and electrode j. (If $R_{ij} \neq R_{ji}$ from the tables, use the larger value for both.) Note that R_{ij} = R(r) evaluated at $r = r_{ij}$, and that R_{ii} = self resistance of the electrode.

3. Inverting the N × N matrix.

4. Summing the elements of the inverse matrix. The ground bed resistance is the reciprocal of this sum.

If the electrodes are all identical and are equally spaced on a circle (this includes all arrangements of identical electrodes, three electrodes in an equilateral triangle, four electrodes on a square), the resistance can be computed as

$$R = \frac{1}{N} \sum_{i=1}^{N} R_{ii} \ .$$

Derivation of the Rubber Sheet Analogy

The vertical deflection, z, of an elastic membrane (lying in the x-y plane) is found by solving the differential equation

$$\frac{\partial^2 Z}{\partial X^2}\left[1 + \left(\frac{\partial Z}{\partial y}\right)^2\right] + \frac{\partial^2 Z}{\partial y^2}\left[1 + \left(\frac{\partial Z}{\partial X}\right)^2\right] - \frac{\partial^2 Z}{\partial X \partial y}\frac{\partial Z}{\partial X}\frac{\partial Z}{\partial y} = 0.$$

If the deflection of the sheet is small (tangent plane kept within 15° of the horizontal) then $\frac{\partial Z}{\partial X} \ll 1$, $\frac{\partial Z}{\partial y} \ll 1$ and the equation reduces to

$$\frac{\partial^2 Z}{\partial X^2} + \frac{\partial^2 Z}{\partial y^2} = 0 \ ,$$

which will be recognized as Laplace's equation.

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[1]Orellana, E., and H. M. Mooney. Master Tables and Curves for Vertical Electrical Sounding. Interciencia, Madrid, 1955, 34 pp.

TABLE A-1. - Self and mutural resistances of various electrodes

Electrode type	Resistance	Mutual resistance
Hemisphere.....	$\frac{\rho}{2\pi a}$	$\frac{\rho}{2\pi r}$
Disk or dragline tub..	$\frac{\rho}{4a}$	$\frac{\rho}{2\pi a}\sin^{-1}\frac{a}{r}$
Ring of wire.....	$\frac{\rho}{\pi \ell}\ \ell n\ \frac{4\ell}{\pi a}$	$\frac{2\rho}{\pi} = \frac{F(i)}{\ell+2\pi r}$ $i = \frac{2\sqrt{\ell r}}{\ell+\pi r}$ $F(i) = \int_0^{\pi/2} (1-i^2\sin^2\Psi)^{-\frac{1}{2}}\, d\Psi$
Rod or borehole casing (homogeneous earth).	$\frac{\rho}{2\pi\ell}\ \ell n\ \frac{2\ell}{d}$	$\frac{\rho}{2\pi\ell}\ \sinh^{-1}\frac{\ell}{r}$
Rod or borehole casing (layered earth).	Use above formulae with-- $1/\rho = \sum_{i=0}^{n} \frac{c_j}{\rho_j}$ $c_j = (1-y^2_{j+1})^{\frac{1}{2}} - \sum_{k=0}^{k=j^{-1}} c_k$ $c_0 = (1-h_1^2)^{\frac{1}{2}}$ $y_j = 1-\frac{1}{\ell}\sum_{k=0}^{k=j} h_k$	

TABLE A-2. - List of symbols

Symbol	Meaning
a	Electrode radius or wire radius.
c	Weighting factor (used with subscript).
h	Layer thickness.
j	Integer subscript.
i	Argument of complete elliptic integral.
k	Integer subscript.
ℓ	Rod, wire ring, or borehole casing length.
n	Number of layers.
r	Distance between constituent electrodes of a bed.
y	Layer thickness (y_o is penetration into bottom layer).
F(i)	Complete elliptic integral.
R	Resistance (with or without subscript(s)).
N	Number of electrodes in ground bed.
π	3.14159...
ρ	No subscript: average resistivity. With subscript: layer resistivity.

TABLE A-3. - Potential-electrode locations for measuring borehole case resistance

Rod length (fraction of current-electrode spacing)	Potential-electrode location (fraction of current-electrode spacing)
0.01	0.618
.1	.617
.5	.602
1.0	.570
1.5	.538
2	.509
3	.462
5	.393

TABLE A-4. - Potential-electrode locations for measuring dragline tub resistance

Tub radius (fraction of current-electrode spacing)	Potential-electrode location (fraction of current-electrode spacing)
0.01	0.618
.1	.630
.3	.665
.5	.718

ELECTRICAL GROUND ROD CORROSION

by

Bruce T. Olenchuk[1] and Wils L. Cooley[2]

ABSTRACT

Electrical grounding is essential for the safe operation of power systems. A low-impedance path to ground is necessary to prevent the possibility of dangerously high potentials in human work areas. If for any reason this ground connection becomes faulty, a serious hazard may exist. One reason for faulty ground connections is ground bed corrosion.

Corrosion of electrical ground rods has plagued the power industry and appeared in coal mine power systems. This paper will investigate ground rod corrosion, its cause, and possible solutions. Included is an evaluation of various ground rods for their ability to resist corrosion under stray current conditions. The first known study of X-it[3] Rod Corrosion is also presented.

INTRODUCTION

Metals continually try to return to the stable energy state from whence they came. Man uses energy in purifying metallic ores to produce metal, hence elevating metal in the energy scheme. It is this energy storage of metal that provides the catalyst for corrosion. Corrosion can be described as the release of stored energy in an attempt to reach an energy equilibrium.

All corrosion is electrolytic in nature. Energy, in the form of electrons, is used for chemical reactions at the metal surface. Because corrosion is electronic, a corrosion circuit, or cell, is formed. Potentials developed at the metal surface give rise to a current (electron flow) causing corrosion. The mere presence of a drop of water on a piece of iron sets up an electrochemical cell causing current flow and thus corrosion.

Ground bed corrosion occurs when the bed becomes a current sink. Interconnected ground beds composed of two or more metals set up a galvanic corrosion cell. Two metals, each at a different energy level, cause a potential difference. This potential difference provides an electron flow (current) necessary for corrosion reactions. Leakage currents in an electrical ground system also contribute to ground bed corrosion. These currents result from potential differences in ground points.

In an electrolytic medium the corrosion rate of a metal is proportional to the current flowing from that metal (5).[3] Observations of coal mine

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[3]Underlined numbers in parentheses refer to items in the list of references at the end of this paper.

FIGURE 1. - Remains of 8-foot by 1/2-inch Copperweld ground rod used as part of mine ground bed.

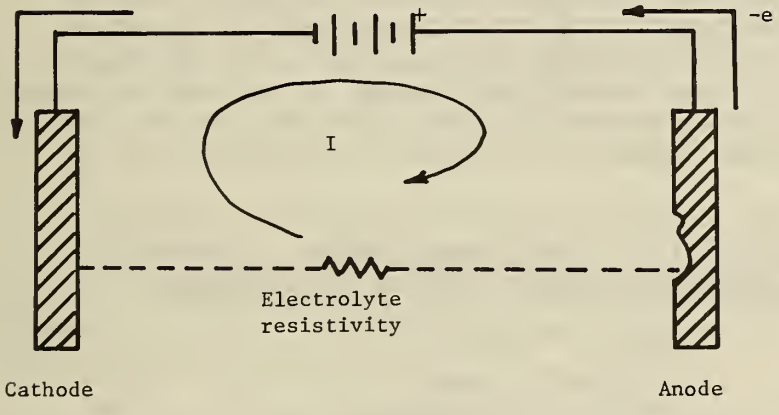

FIGURE 2. - Basic electrolytic corrosion circuit.

electrical ground systems indicate currents from 0 to 10 amp flowing during normal mine operations. By law, current flow in excess of about 15 amp is considered unsafe and constitutes a fault condition. However, currents below the ground fault trip point are unrestricted (13). The possibility of current flow in the ground system less than the ground fault trip point for extended periods increases the likelihood of severe corrosion. Figure 1 shows the catastropic results of unchecked ground bed corrosion.

ELECTROLYTIC CORROSION OF GROUND BEDS

Background

Three things are needed to define electrochemical corrosion of a metal. The electrochemical system must have an anode and a cathode, which must be connected by some ionic medium. To complete the electrical circuit, the anode and cathode must be externally connected with a low-impedance path or source (fig. 2).

The corrosion process is electrochemical because of the continual change between electronic and ionic flow. Electrons flow from anode to cathode, while conventional current flows from cathode to anode. Corrosion occurs at the anode-ionic interface through the process of oxidation, the removal of electrons from metal atoms. Examples of oxidation reactions are--

$$Zn \rightarrow Zn^{++} + 2e^{-}$$

$$Al \rightarrow Al^{+++} + 3e^{-}$$

$$Fe^{++} \rightarrow Fe^{+++} + e^{-}$$

These freed electrons travel through the low-impedance path to the cathode, where they are involved in the complementary process of reduction. Examples of reduction reactions are--

$$H^{+} + e^{-} \rightarrow \tfrac{1}{2} H_2$$

$$Cu^{++} + 2e^{-} \rightarrow Cu$$

$$Fe^{+++} + e^{-} \rightarrow Fe^{++}$$

Thus the simultaneous oxidation-reduction reactions complete the electrochemical circuit.

The speed and direction of electron flow along the external connection will determine the corrosion rate for each metal. Insertion of an electronic source increasing electronic movement toward the cathode results in increased corrosion. A steady flow of electrons in a cathodic direction (dc current) is very conducive to corrosive action. If alternating current (electron flow) is applied, electron flow alternates every half cycle. This means that each electrode alternates from an anodic to a cathodic state. Ideally, with the application of pure ac, neither electrode is purely anodic or cathodic; thus no corrosion should occur. Realistically, the presence of a pure alternating current reduces a metal's corrosion rate typically to 1 pct that of the RMS equivalent direct current (14). The tendency of a metal to corrode is related to its reduction potential, which has been determined for many substances (table 1). The more negative the reduction potential, the greater the corrosive activity.

TABLE 1. - Reduction potentials of some common metals. Increasing reduction potentials denotes decreasing corrosion.

Au^{+} (gold)	+1.68	Sn^{+2} (tin)	-.14
Pt^{+2} (platinum	+1.20	Fe^{+2} (iron)	-.41
Ag^{+} (silver)	+.80	Cr^{+2} (chromium)	-.56
Cu^{+2} (copper)	+.34	Zn^{+2} (zinc)	-.76
H^{+} (hydrogen)	.00	Mg^{+2} (magnesium)	-2.38
Pb^{+2} (lead)	-.12		

Corrosion Current Path

The corrosion current path to be described comes from a typical, low-voltage power distribution system for underground coal mine operations. Although this discussion uses the mine power system for illustration, it could easily apply to any power system using a combination of dc and ac power.

At the substation, depending on available power, approximately 38 kv is brought to the primary side of a Δ-y connected transformer (fig. 3). Lightning arresters are located here at the primary side and grounded through a system ground. On the secondary side approximately 7.2 kv is taken underground via the borehole. By regulation, the center of the y is grounded through a resistor so as to limit fault current to not more than 25 amp (5); this ground is termed the safety ground. The earth side of the resistor is

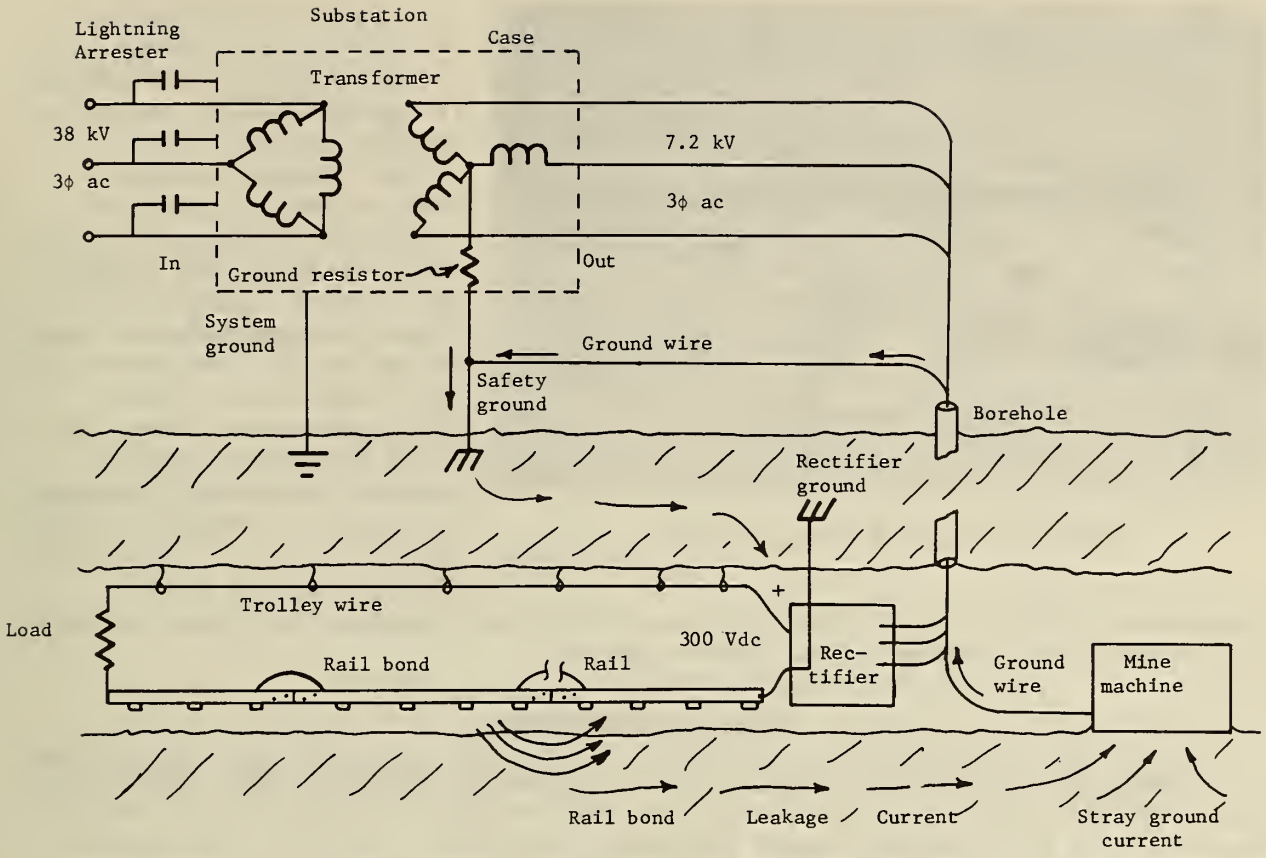

FIGURE 3. - Possible corrosion current path for underground mine power systems.

carried into the mine along with three-phase power and attached to all machine frames. It should be noted that most machines are in intimate contact with earth during mine operations.

For ease of operation and complexity, most underground mines use a dc haulage system to transport men and coal into and out of the mine. The mine trolley system uses rectified dc, the trolley wire above carries current away from the rectifier, and the track itself is used as the return current path. In some trolley systems the negative side of the rectifier is also grounded. A problem arises in using the rail itself as a current conductor. To simplify installation, the rail joints are not welded; however, rail bonding is used to insure a good electrical connection. Rail bonds often consist of a 4/0 copper-stranded wire tack-welded to each rail (fig. 4). Through the course of events rail bonds become broken, worn, or in some cases vanish. Disconnected rail bonds introduce a resistance in the return current path, allowing some current to flow via the ground back to the rectifier.

Once the current enters the ground, a number of possible routes are available. One such route, prompting ground bed corrosion, will be described. Remembering that all mine machinery comes in contact with earth, one possible route would be from the rail to a mine machine, down through the safety ground bed via the safety ground wire, and back to the rectifier (fig. 3).

FIGURE 4. - Mine dc trolley rail bond.

In the described circuit the safety ground becomes anodic, thus making it susceptible to corrosion. To make matters worse, ground leakage currents, both ac and dc, tend to circulate in the ground system, adding to the ground bed corrosion problem (6). These leakage currents could be due to (1) imbalances in the three-phase system, (2) electrolytic cells set up by different metallic grounds connected together, (3) telluric induced currents (7), or (4) mild nonclearing faults during operations (fig. 5). Whatever the cause, the fact remains that these currents are present and flowing in the ground system.

Field Measurements

There is a Bureau of Mines mine car roadway at Bruceton, Pa. The Bruceton trolley system, which is entirely on the surface, is nevertheless representative of a corrosion circuit previously described (fig. 3). Three-phase ac power is rectified, providing 300 volts dc to run a resistive-controlled locomotive. Current is passed from the rectifier to an aboveground trolley wire and returned via the rail (fig. 6). The safety or system ground bed is connected to the negative side of the rectifier and to the rectifier's metal case. Railbonds were nonexistent, suggesting large leakage currents.

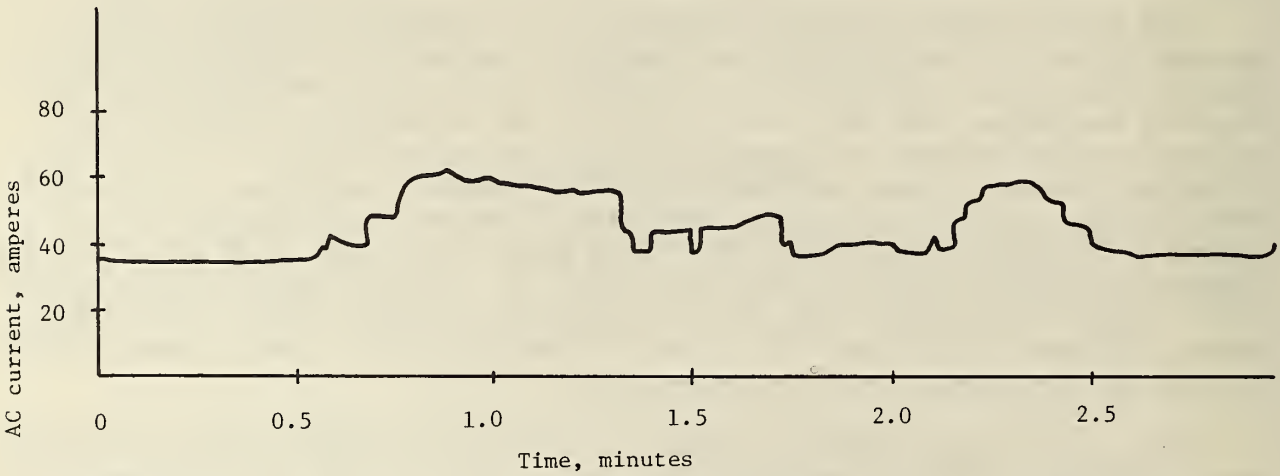

FIGURE 5. - Ground current reading, recorded by Penn State, January 9, 1975, Greenwich Collieries, South mine.

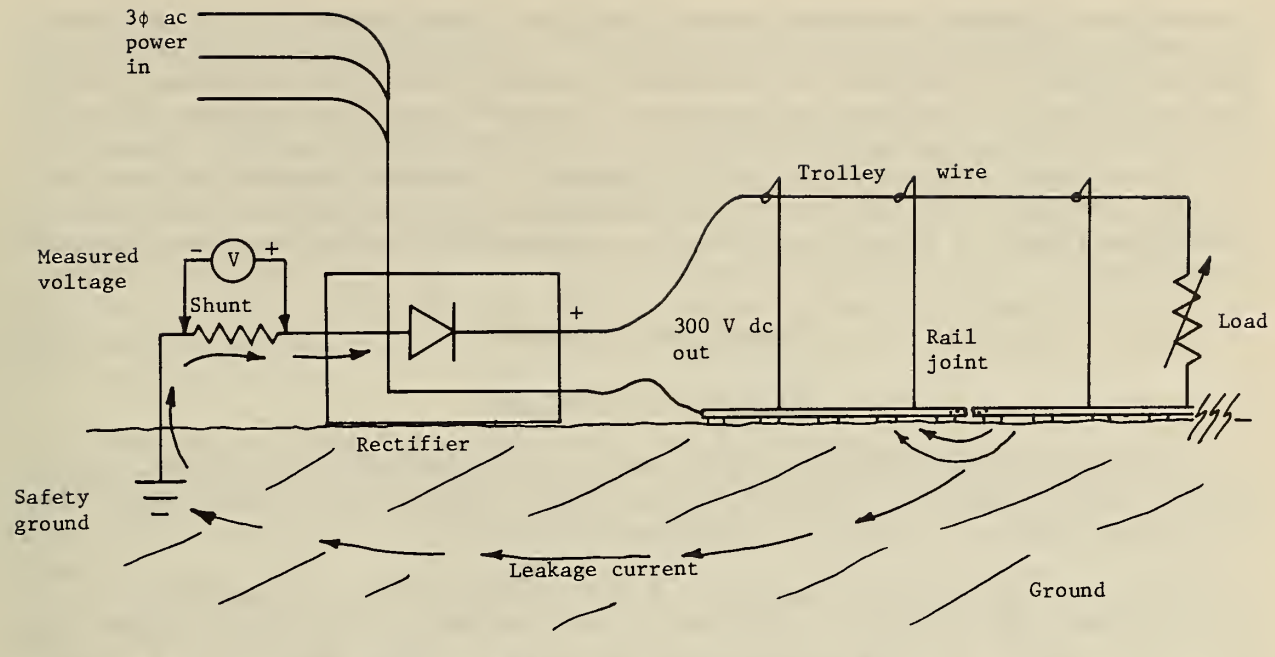

FIGURE 6. - Test trolley schematic, Bruceton, Pa.

With power removed a series shunt was placed in the ground wire, and current was measured as a corresponding voltage drop. Leakage current in the ground was proportional to the quantity of current used by the trolley

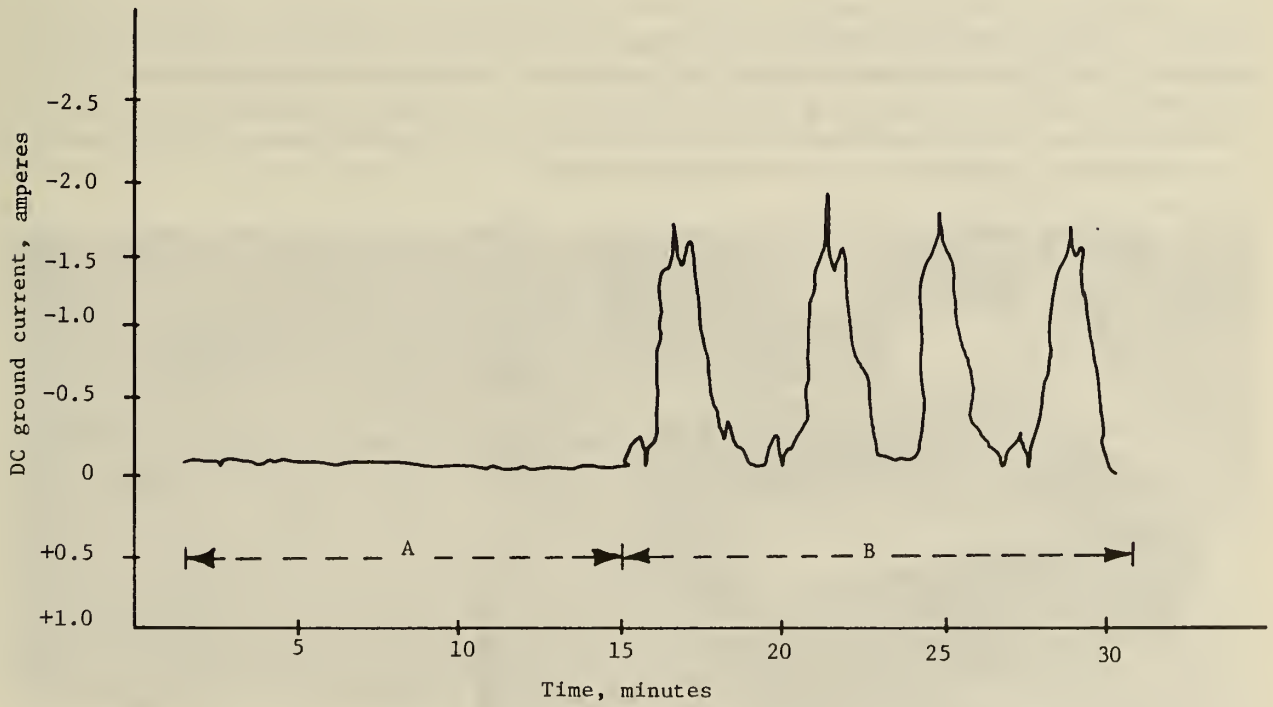

FIGURE 7. - Dc current leakage, Bruceton, Pa., test track, September 7, 1977 (A, locomotive stopped; B, locomotive moving).

locomotive. Leakage currents ranged from 0 to 2 amp depending on the amount of current drawn from the rectifier (fig. 7). Contrary to the ground bed corrosion circuit of figure 3, all leakage current passed from the ground bed to the rectifier. Even though no evidence of severe corrosion existed at Bruceton's test track, this experiment proved that substantial currents circulate in the dc rail haulage system. The direction of leakage current at Bruceton can be attributed to the absence of additional system grounds. Given the right conditions in a mine environment, a ground bed corrosion circuit is very possible.

GROUND ROD EVALUATION

Simulated Ground Beds

To effectively evaluate a large number of ground rods in a short period, a simulated ground bed was built indoors, thus eliminating stray current hazards and providing controlled environmental variables.

The test ground beds consisted of three wooden boxes filled with soil. Each box was constructed of 3/4-inch plywood and was 3 feet wide, 3 feet long, and 1 foot deep. To help retain moisture, each box was coated with a special watertight paint. Before the addition of soil, a number 6 solid copper wire was tacked to the inside perimeter and brought outside through a hole drilled in one side (fig. 8). This copper wire became the cathode of the electrolytic corrosion cell.

Soil was placed in each of the three boxes. Each box was watered and salted, using ordinary rock salt, to provide a fairly conductive electrolytic medium. Early experience showed that moisture loss due to evaporation occurred rapidly, increasing soil resistivity. To help eliminate moisture loss and keep soil resistivity fairly constant, a plastic cover was placed over each box, producing a moisture barrier.

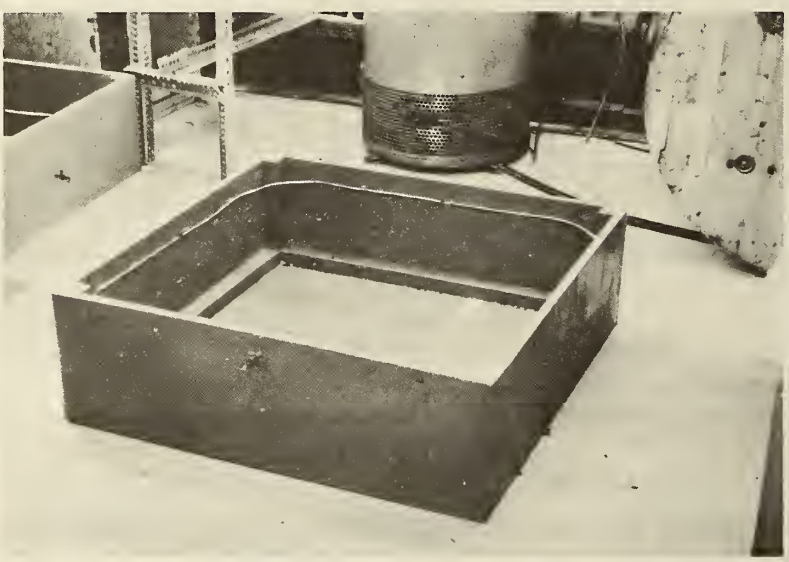

FIGURE 8. - Simulated ground bed box without soil.

Test Procedure

Tests consisted of placing approximately 1-foot-long electrode samples in the center of the soil box. A 20-volt, 25-amp dc power supply was used to impress current from the sample electrode (anode) to the copper wire surrounding the box perimeter (cathode). A circuit of this nature could also be described as cathodic protection of the copper wire. A precision shunt (10-amp, 50-mv) was placed in series to record the current as a corresponding voltage drop.

The soil was watered and salted prior to testing and remained covered with plastic throughout each test. Each rod was cleaned and weighed prior to current passage. Length of current passage ranged from days to weeks, depending on the rate of corrosion. At the conclusion of each test the rod was carefully removed and examined for corrosion. Corrosion products were removed, and each rod was scrubbed with a commercial cleanser and nylon brush. No attempt was made to remove tightly bound corrosion products. After thorough cleansing, the rod was dried and weighed (9). Rods tested in this manner included 1/2-inch Copperweld rod, 5/8-inch steel reinforcing rod (rebar), 5/8-inch stainless steel rod (No. 304), 5/8-inch galvanized steel rod, 1/2-inch Duriron (SiCrFe) rod, and 1/2-inch graphite rod; 4/0 stranded aluminum wire was also tested.

Three specialized electrodes were tested: Rebar in concrete, graphite with coke breeze backfill, and Z-it rod. Rebar in concrete consisted of a steel reinforcing rod backfilled with concrete (fig. 9). This combination is suggested in recent literature to be a possible solution to low-resistance grounding (2). The concrete-steel electrode was left idle in moist soil for 1 week to allow moisture migration into the porous concrete, decreasing concrete resistivity (18).

Graphite surrounded by coke breeze is recognized as a standard installation method (1). Coke breeze provides lower contact resistance and increased chlorine gas ventilation. This test electrode consisted of a graphite rod backfilled with a rather granular coke breeze.

X-it rod has recently arisen as an answer to low-resistance earth grounding (15); these rods consist of type K copper or galvanized tubing, 2-1/8-inch in diameter, capped at both ends, and filled with salt and a special hydrophilic substance. There are four holes at the top and bottom of each rod; instructions request that the top holes always remain aboveground and uncovered. A sample X-it rod was obtained from X-it Rod Corp. This custom-designed rod duplicated every aspect of a standard X-it rod except length. Due to the 1-foot depth of the simulated ground beds, the sample X-it rod was reduced in length to 18 inches (fig. 10).

FIGURE 9. - Concrete-encased steel reinforcing rod used as a grounding electrode.

Data Collection

An accurate time record of current passing through each anode was captured by one of two chart recorders. The current passed at any given time is proportional

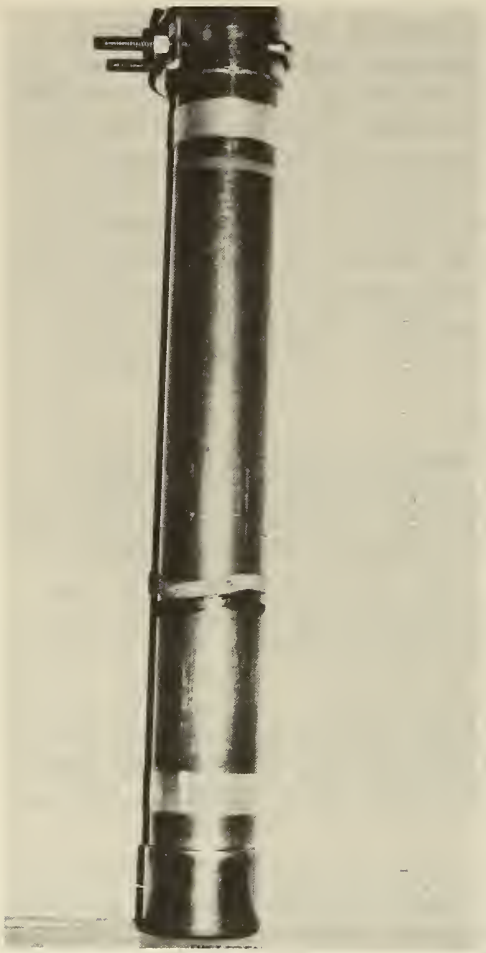

FIGURE 10. - Custom-designed X-it rod used for corrosion studies.

to the corrosion rate. Integration of the current waveform gives the total charge passed. From the calculated charge expressed in ampere-hours and the electrode's weight loss in grams, a corresponding corrosion rate in grams per ampere-hour is obtained. By calculating the surface area (S) of each electrode,

$$S = 2(\pi)rl + 2(\pi)r^2,$$

charge density is expressed in ampere-hours per square centimeter (table 2). Observations were made before, during, and after each test. A brief description of each rod tested and corresponding observations follow:

Copperweld rod.--The rod used showed no visible signs of corrosion activity prior to testing. The rod was driven 8-3/4 inches into the test soil and connected to the dc supply with a standard ground rod connector. The soil remained moist for the duration of the test. During current passage green copper oxide (Cu_2O) appeared at the base of the exposed rod. Current passage continued for 45 days, ranging from 0 to 4 amp. At 31-1/2 days into the test, the rod grew thin near the soil surface, and shortly thereafter the rod severed at the soil surface, leaving a portion of rod buried below ground (fig. 11). After this separation the original circuit was no longer intact; however, the exposed section lay touching the soil, causing current flow to continue. Upon removal the below-soil section was covered with a black, carbonaceous, greaselike substance. After scrubbing, the rod showed a very fine wirelike narrowing where final separation occurred. The buried section showed numerous pits and general deterioration. Including both sections, the rod length after corrosion was 11-7/8 inches.

TABLE 2. - Ground Rod Current Passage Results

Rod	Period, days	Ampere-hours	Weight loss, grams	Corrosion rate, g/amp-hr		Charge density, amp-hr/cm^2
				Measured	Theoretical	
Copperweld.....	45	107.9	143.7	1.33	0.7	0.87
Steel rebar.....	7	110.8	69.8	.63	.7	.71
Steel rebar in concrete	14	129.5	94.9	.73	.7	.83
Graphite in soil.....	2	126.8	21.5	.17	NA	1.00
Graphite in coke.....	7	222.8	7.75	.03	NA	1.76
Duriron (SiCrFe).....	4	297.2	55.0	.19	NA	3.45
Galvanized steel.....	8	467.5	207.8	.44	.7	3.00
X-it rod.....	14	470.7	570.0	1.21	1.19	.57
Aluminum wire.....	8	88.8	51.3	.58	.34	.40
Stainless steel.....	8	404.11	124.4	.31	.65	2.59

NA Not available.

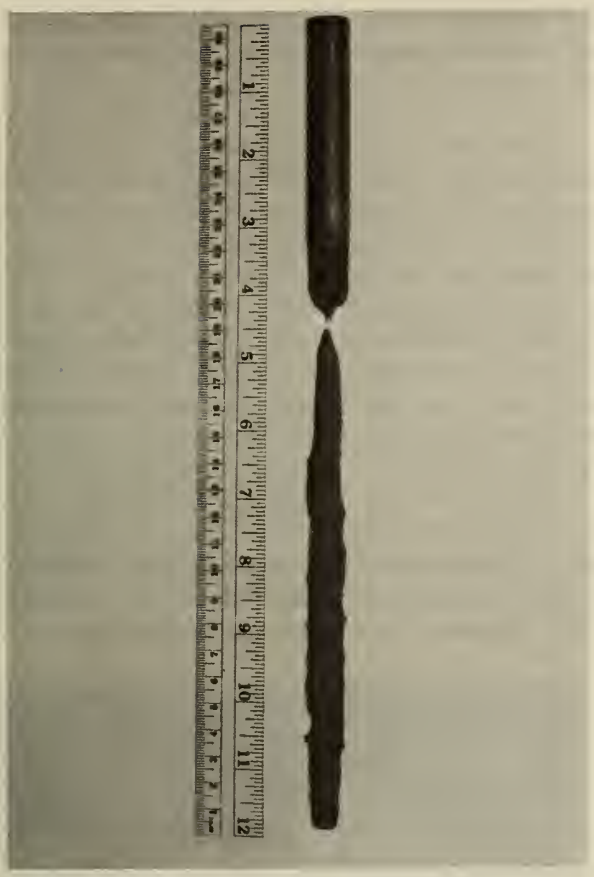

FIGURE 11. - Copperweld rod following corrosion test.

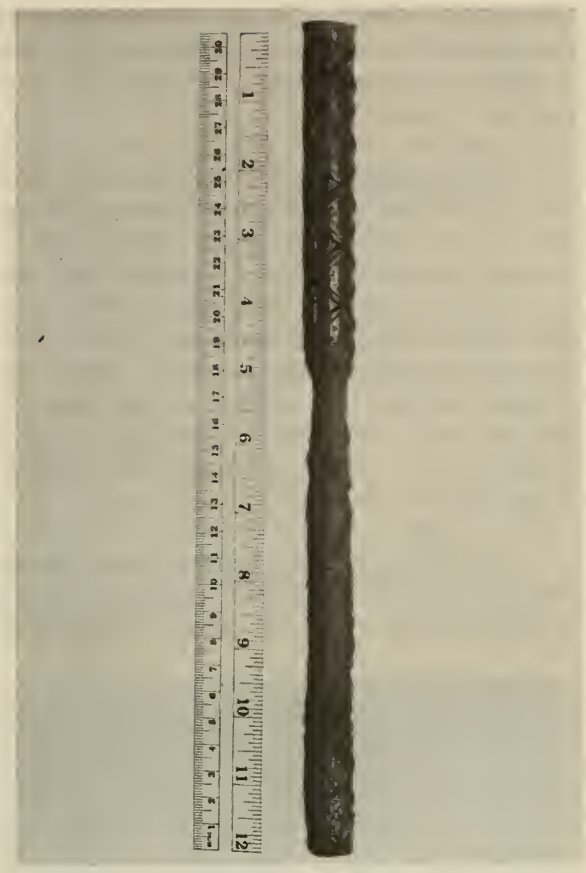

FIGURE 12. - Steel reinforcing rod after corrosion test.

Steel reinforcing rod (rebar).--Before testing, some corrosion (iron oxide) was noted on the rod's surface. The test rod was driven 7-1/4 inches below the soil surface, and current was passed for 7 days. Current values ranged from 0.5 to 4 amp. During current injection a black, carbonaceous substance appeared at the exposed rod's base. After the test's conclusion a circular iron deposit surrounded the steel rod. Soil remained moist throughout the experimental period. Upon removal a black, carbonaceous, greaselike substance clung to the rod; after cleansing, the rod showed localized corrosion near the soil surface with extensive pitting elsewhere (fig. 12). Length of the corroded steel rod was slightly less than 12 inches.

Galvanized steel.--A 12-inch-long rod was driven 9 inches into the test soil; current ranging from 0.8 to 6 amp was passed for 8 days. During current passage the presence of chlorine gas was noted by its pungent odor. A black greaselike substance appeared at the base of the exposed rod, and gaseous bubbles were observed near the rod. Current passage was very heavy throughout the experiment, and soil moisture remained high. On the eighth day current flow was stopped, and the rod was removed. Adhering to the outside surface was a dark brown oxide layer (ZnO). The oxide layer was easily peeled from the rod, exposing a black carbonaceous liquid. After thorough scrubbing,

localized corrosion was noted near the soil surface and at the electrode base. Corrosion at the soil surface had worn the rod dangerously thin, suggesting a possible break with further current flow. Corroded rod length was 11-1/4 inches (fig. 13).

Stainless steel.--A 12-inch-long electrode was cut of 304 stainless steel, and 9-1/8 inches of the rod was placed into soil for corrosion analysis. Current passage was heavy, ranging from 0.7 to 5 amp and lasting for 8 days. During current flow a pungent chlorine gas odor was evident, and a black greaselike substance appeared at the base of the exposed rod. Removal of the rod revealed a surface oxide layer (Cr_2O_3), which was easily peeled away. Under the oxide layer was a carbonaceous liquid. After scrubbing, the rod showed severe pitting and necking (corrosion at the soil surface) but remained bright and lustrous. The soil retained its moisture content throughout the experiment. The corroded rod length for stainless steel was 11-7/8 inches (fig. 14).

Duriron (SiCrFe).--The rod used in this experiment was only 8-1/4 inches long, and 6-3/4 inches remained below the soil surface. Because of its small diameter and brittle nature, the rod was not driven into the soil; rather, it

FIGURE 13. - Standard galvanized steel ground rod following corrosion test.

FIGURE 14. - Stainless steel ground rod following corrosion test.

was placed in a larger diameter hole and backfilled with soil. Standard ground rod clamps could not be used; therefore, a sufficiently large alligator clip provided the electrical connection. Current passage was extremely high (2 to 5.8 amp) and lasted for 4 days. The shortened time period was used for fear that the rod would overcorrode. The pungent odor of chlorine gas was very much present during the experiment, and black greaselike material formed at the exposed rod's base. The plastic box cover was removed at the test's conclusion, revealing an iron ring deposit a short distance from the rod. Soil adjacent to the rod appeared dry and yellowish in color. Moisture content in the rest of the box remained high, however. Rod removal revealed a large perforated surface oxide layer which was easily removed. Under the oxide layer (SiO_2, Cr_2O_3) was a black carbonaceous liquid. Thorough washing revealed uniform corrosion with no visible necking or pitting. The rod's length after corrosion was still 8-1/4 inches (fig. 15).

Graphite in soil.--Eight and one quarter inches of a graphite electrode was placed in a larger diameter hole and carefully backfilled with soil. The 1/2-inch rod diameter was too small for conventional ground rod clamps, as a large alligator clip was used. Current passage ranging from 4 to 5 amp lasted for only 2 days owing to a break in the graphite rod. A very high concentration

FIGURE 15. - Duriron ground rod following corrosion test.

FIGURE 16. - Graphite ground rod following corrosion in soil.

of chlorine gas was produced during the test, causing the need for exhaust fans. Rod breakage occurred at the surface level, disconnecting the corrosion circuit. Removal of the plastic cover revealed yellowish soil adjacent to the rod and pieces of graphite in the soil. A sizable piece of graphite was removed from below the soil surface. The combined length of both pieces was 10-3/4 inches (fig. 16). One related observation was the oxidation of metals placed in close proximity to the corroded graphite rod, suggesting continued chlorine gas emission.

Aluminum.--A 21-1/2-inch section of 4/0 stranded aluminum wire was used for corrosion testing. Nine and one half inches of the wire was buried in soil, and a large alligator clip was used for electrical connection. Current levels ranged from 0.1 to 4.8 amp for 8 days. The larger current levels appeared during initial startup; current rapidly decayed with time. A constant current of approximately 0.5 amp continued throughout a major portion of the test period. During current passage a white saltlike substance appeared at the exposed wire base. The same substance became yellowish in color with age. At the test's conclusion the aluminum wire was removed, revealing localized corrosion near the soil surface which caused filaments of wire to separate from the main trunk. The wire surface was covered with a milkish white and red substance. After thorough cleansing, the below-soil section appeared crusty and dull gray in color, suggesting the enhanced presence of aluminum oxide (Al_2O_3). The soil remained moist throughout the experiment. After corrosion the wire length was 18-1/2 inches (fig. 17).

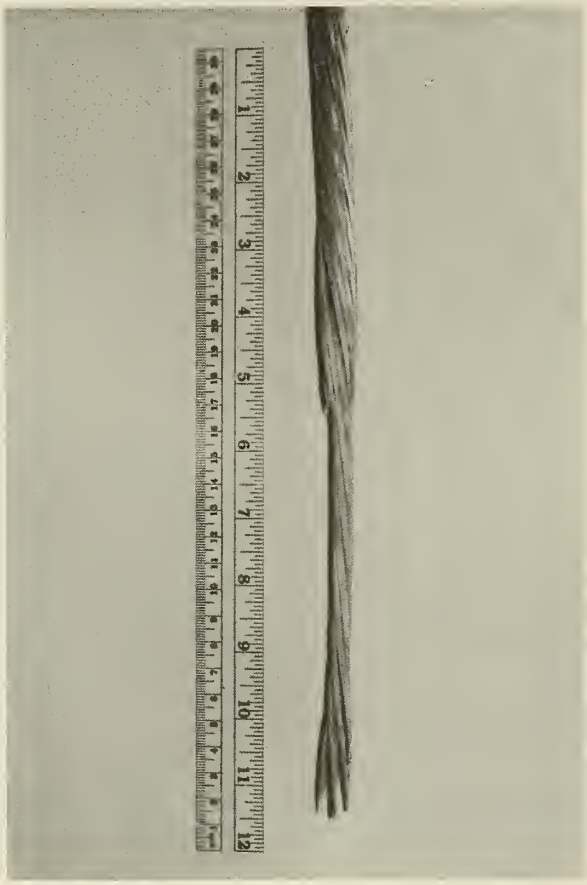

FIGURE 17. - Aluminum wire (4/0) following corrosion test.

Graphite in coke breeze.--A variation of the graphite electrode, graphite backfilled with coke breeze, is one of three special electrodes tested. Coke breeze consists of finely ground coke. The coke breeze available for testing was more granular, however. A 12-1/4-inch-long graphite rod, identical to the one used for graphite in soil, was placed in a 4-1/2-inch-diameter hole and backfilled with granular coke breeze (fig. 18). Four and one quarter inches of graphite rod was exposed above the soil level. Current passage was light, ranging from 0.2 to 6 amp for 7 days. During the test period some chlorine gas was noted, but the air concentration was low, posing no health hazard. After 3 days of low current flow, water was added to the soil-coke interface in an attempt to lower circuit resistance. Following the addition of water, current

FIGURE 18. - Graphite ground rod backfilled with granular coke breeze.

flow increased and remained high for the remainder of the test. After 7 days the rod was removed. Very little corrosion or weakening was noted along the electrode body; however, 1-3/8 inches of the rod's base was lost. The after-test rod length was 10-7/8 inches (fig. 19).

Steel rebar in concrete.--The second of three specialized electrodes consisted of a 12- by 5/8-inch steel reinforcing rod encased in concrete. Seven inches of the steel rod was imbeded in concrete, 8 inches deep and 6 inches in diameter. The concrete-steel electrode was constructed in soil

FIGURE 19. - Graphite rod after corrosion test in coke breeze.

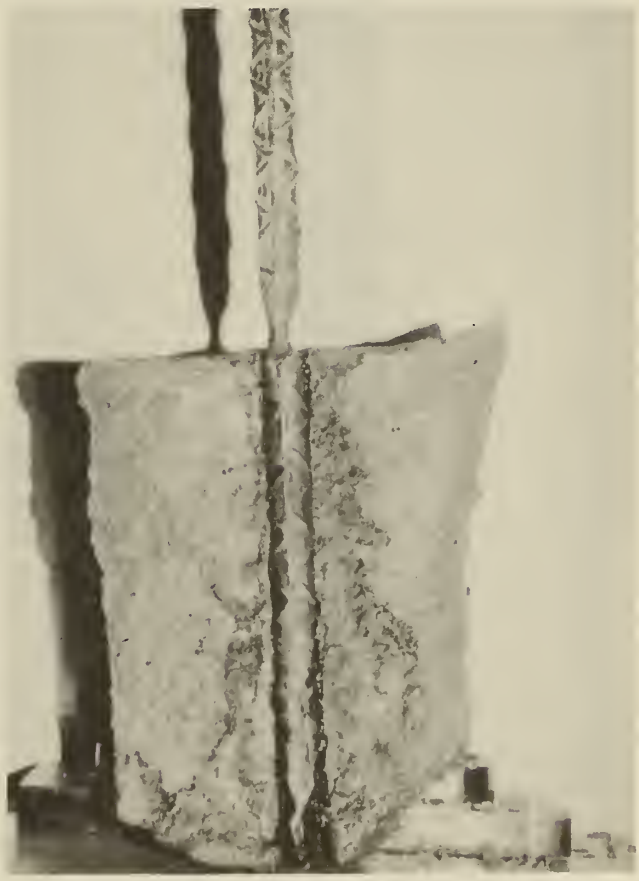

FIGURE 20. - Concrete-encased rebar following corrosion.

(fig. 9). The "concrete" used was actually a patching mix with the trade name Sakrete sand mix. After formation the cement rod was allowed to harden for 2 days with the plastic box cover removed. To insure adequate concrete moisture during experimentation, the hardened electrode was watered and allowed to sit covered for 7 days. Current passage was very mild, ranging from 0.2 to 0.6 amp, and was continued for 14 days. At the experiment's conclusion the plastic cover was lifted, revealing a symmetrical split in the cement base. The concrete electrode was extracted in two pieces, one half adhering to the steel rod. Iron deposits were visible throughout the concrete, and a black, carbonaceous, greaselike substance coated the steel rod. After washing the intact concrete-rod section, it was noted that localized corrosion occurred at the concrete surface and rod base (fig. 20). Moderate pitting was noted along the encased rod section; after-corrosion length was 11-13/16 inches.

X-it rod.--A sample X-it rod, 18 by 2-1/8 inches, was custom-made for these experiments by C. J. Reinmuller, X-it Rod Corp. president. The electrode was placed 9 inches into the box and backfilled with soil. The rod was left dormant for 18 days to allow the patented salting action time to start. To observe the self-salting action, rod-soil resistance was monitored us using the Bison meter and three-electrode method (table 3). When the rod-soil resistance stabilized, current injection was started. Current flow was high, 0.6 to 4 amp, lasting for 16 days. Green copper oxide appeared at the exposed rod's base, thickening with time. Soil near the rod became dry and hard, making rod removal difficult. Corrosion left the rod walls very thin, and breakage occurred while attempting removal. In all, three sections of rod were recovered (fig. 21). The rod's internal salt appeared dry and was easily lost during removal. A closer examination of the split rod revealed fiberglass in the proximity of both exit holes with loosely packed salts in between. Copper oxide clung to the outer skin of the buried rod. After scrubbing, the rod walls were found to be paper thin. Localized corrosion was greatest near the surface and bottom. One additional observation is that the corroded X-it rod pieces, still retaining salt, continued to draw moisture from the air even after corrosion.

FIGURE 21. - X-it rod following corrosion.

TABLE 3. - Rod-to-soil resistance of X-it rod prior to corrosion

Day	Rod-soil resistance, ohms
Installation.....	4.05
2.....	3.80
3.....	3.75
10.....	3.58
12.....	3.64
18.....	3.71
After corrosion.....	6.87

Results and Discussion

Each metallic anode tested produced a metallic oxide skin. Some oxides caused their anodes to become noble, raising cellular potentials and producing gaseous oxygen and chlorine. The soil concentration of chlorine ions was very high owing to external salting, thus increasing the production of Cl_2 and its attack on metallic oxides. A carbonaceous substance appeared repeatedly around ground rods with high iron content. It is believed that this substance is iron oxide, also very dark black in color (10).

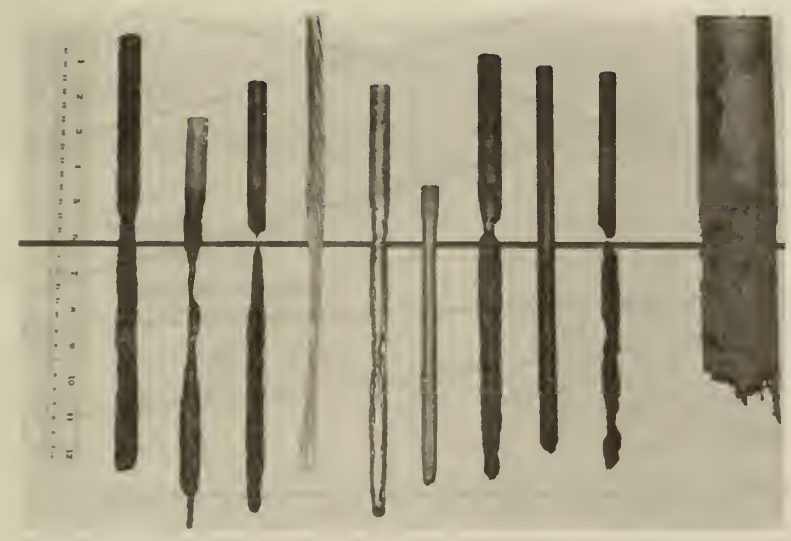

FIGURE 22. - Composite of all ground rods tested following corrosion. Black line indicates soil level.

Every metal rod tested, except SiCrFe, showed localized corrosion at both the surface (necking) and the rod base (fig. 22). With continued current flow metal rods severed close to the soil surface, indicating extreme localized current flow. Necking or rapid localized corrosion above the surface is described by Fink; the phenomenon is caused by a constant bathing of that area by corrosion products pushed up from below (3). The area directly above the electrolyte surface does not produce thick oxide layers owing to lack of current flow; therefore, this area of the rod is very susceptible to attack by corrosive agents generated below. In the rod configuration the maximum current density is located at the

base, which is also the area of lowest oxygen concentration; thus oxide formation is retarded (4), and accelerated corrosion of the rod's base is expected.

All but one of the rod currents were noticed to decrease with time owing to dc polarization (fig. 23). One cause of polarization is the decreasing presence of ions necessary for anodic reactions. As accelerated reactions take place, a buildup of products occurs, gradually restricting reactants from reaching the electrode surface. Because the current in the electrolyte cell is dependent on this electronic-ionic exchange, the gradual decrease in reactant is reflected in a gradual decrease in current flow (12).

An experimental corrosion rate was calculated for each electrode from the weight loss and the charge passed (table 2). Because the corrosion rates are based on charge, the length of time a rod is corroded is unimportant. It can be argued that such corrosion rates are very specific for the type soil and procedure used; this statement is true. If these same rods were tested under different experimental conditions, the results would not remain constant. In dealing with soil electrolytes and corrosion cells, it is difficult to guarantee repetitive results. If all rods are exposed to similar conditions,

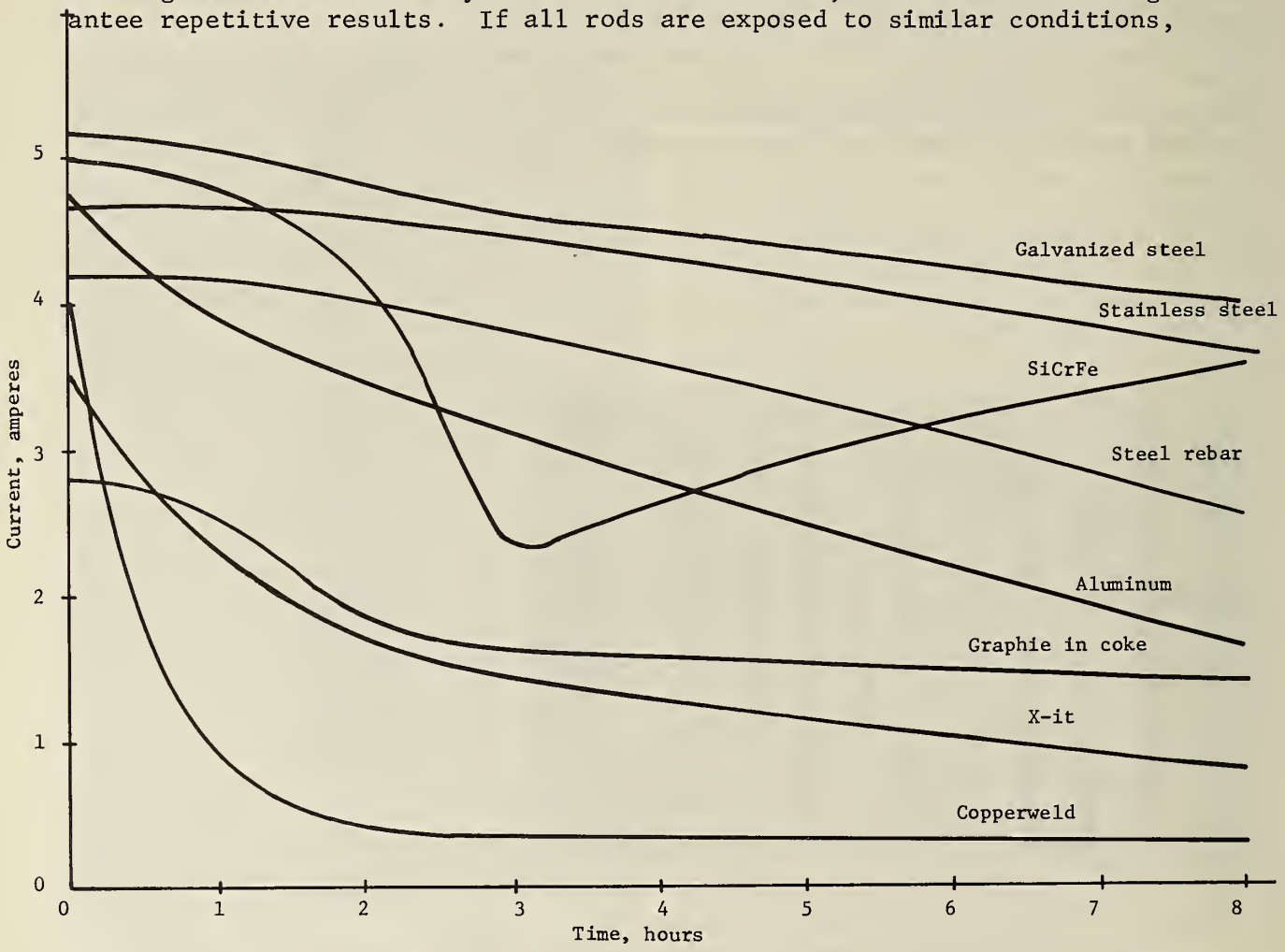

FIGURE 23. - Initial current passage versus time for all ground rods tested. SiCrFe exhibited oscillatory response.

however, a comparison is valid. Although corrosion rates cannot be taken as absolute, they provide a good indicator as to a rod's behavior in a salted, soil environment with moderate current flow. Table 4 provides a comparison of all rods tested according to experimentally determined corrosion rates. The table remarks as to the practical usage of each type of rod. Some rods, such as graphite, are extremely resistant to corrosion but are very difficult to handle; in fact, of the three rods most resistant to corrosion, not a single one is without installation complications. If a severe ground bed corrosion problem exists, the added expense of installing such rods may pay for itself in the future.

TABLE 4. - Comparison of tested ground rods

Ground rod	Measured corrosion rate, g/amp-hr	Usage comment
Graphite in coke.....	0.03	Graphite is extremely brittle. Requires special installation procedure.
Graphite in soil.....	.17	Not recommended without adequate ventilation due to chlorine gas attack.
Duriron (SiCrFe).....	.19	Extremely brittle. Requires predrilled hole. High current density possible. Very uniform corrosion.
Stainless steel.....	.31	High current density possible. Fairly expensive.
Galvanized steel.....	.44	Currently used ground rod. Easily installed. High current density possible.
Aluminum.....	.58	Low current density. Very ductile.
Steel rebar.....	.63	Used as ground rods. Very inexpensive.
Steel rebar in concrete	.73	Previously used for grounding. Requires extensive installation if no reinforced concrete structure exists. Can cause weakening and even cracking of concrete structures.
X-it rod.....	1.21	Requires special installation. Very expensive.
Copperweld.....	1.33	Most commonly used ground rod. Highly corrosive.

Theoretical calculation of corrosion rate was attempted using total charge passed and Faraday's law.[4] The majority of rods tested were alloys. Frequently one metal constituted a large percentage of the total rod, however.

[4]Use of Faraday's Law for metal loss introduces a slight error due to the presence of side reactions and erosion.

in an attempt to predict metal loss it was assumed that the dominant metal was responsible for a majority of the weight loss. No prediction was attempted in the case of insoluble and special electrodes. Results were fairly close for alloys with one high percentage metal (steel); however, results for plated and alloy metals with no high percentage component (Copperweld and stainless steel) proved useless.

CONCLUDING REMARKS

Ground Bed Corrosion

All electrochemical corrosion is caused by metal acting as a dc current sink in an electrolytic medium. At the metal electrolyte interface of a corrosion cell, metal atoms are lost through oxidation. The amount of metal lost is a function of the metal and the amount of current passed. Two forms of ground bed corrosion are possible, galvanic and electrolytic. Galvanic corrosion can be described as corrosion caused by an internally developed current source. When two dissimilar metals or electrolytic concentrations are connected, a corrosion cell results. This cell generates its own current, causing metal dissolution. Electrolytic corrosion is corrosion resulting from an outside current source, such as stray, fault or induced currents. Very likely both corrosion mechanisms are active in ground beds; however, this research effort concentrates on the latter.

Field studies done by Penn State and West Virginia Universities have shown significant amounts of leakage current in the ground system. Such currents can be attributed to faulty track returns in the dc haulage system, unsymmetrical cables inducing currents in the ground wire, galvanic cells set up by nonuniform metallic grounds, and small nonclearing fault conditions.

Solutions to ground bed corrosion are not ones of elimination; rather, they tend to be methods of minimization. Gold, silver, and platinum are well known noncorroding electrodes, but their cost is prohibitive. Therefore man-made inert electrodes emerged to decrease expense while retaining an inert quality. Electrodes such as platinum-plated titanium, lead with platinum inserts, and SiCrFe exhibit these qualities. Using nonmetallic materials for electrodes (for example, graphite) and backfill (for example, coke breeze and concrete) is also a common practice.

Without getting too elaborate or expensive, solutions are available that use existing ground bed materials. To minimize galvanic corrosion, all interconnected ground beds should be composed of a similar metal. Since mine machinery is in intimate contact with earth and is necessarily connected to the ground system, perhaps all ground beds should be composed of steel. Use of coke breeze backfill, even with standard grounding electrodes, will reduce corrosion (5). Additional studies using standard ground electrodes and coke breeze reveal corrosion reductions of 50 pct. Monitoring ground beds for signs of corrosion presents yet another solution. By continuously and noninvasively monitoring ground bed resistance, current injection, or rod shape, evidence of corrosion will appear.

Ground Rod Evaluation

Tests were conducted to analyze possible ground rods and compare their corrosion rates in soil. Simulated ground beds in wooden boxes were used. Dc current was injected into sample rods placed in the soil boxes. Corrosion rates were determined for each rod by weight loss and when possible by Faraday's law. Results indicate that the commonly used ground rod materials are among the most corrosive. As expected, graphite in coke breeze was the least likely to corrode. Electrodes possessing the best corrosion resistance tended to be very difficult to handle and install. Stainless steel stood out as a compromise; it was adequately corrosion resistant and retained the strength and durability needed for ease of installation. If one must use a commercially available ground rod, galvanized steel is the least corrosive.

One common practice is to employ reinforced concrete structures as ground electrodes. Many papers have sanctioned the use of foundations and support structures as low-resistive ground connections (11). Further reading reveals concern over concrete cracking and damage to structures due to electrolytic corrosion (2). The evaluation test done on a concrete-encased steel rebar supported the latter suspicion. The concrete did indeed rupture, and corrosion ensued. It is speculated that gas buildup at the concrete-metal interface causes weakening and cracking of the concrete. Until further long-range studies are done on the effects of concrete-encased electrodes, it is these researchers' opinion that they should be avoided.

The corrosion rate of X-it rod was evaluated for the first time. This rod's unique feature is the ability to salt itself. Salt and a hydrophilic substance reside inside a hollow copper or galvanized tube. Moisture in the air is attracted by the hydrophilic substance and carried by capillary action to the rod's base. Salt is dissolved in the water as it flows down the tube. At the rod's base the salt water solution slowly leaches into the soil. This patented technique seems to be very effective in lowering rod-soil resistance. In this study the interest was placed on X-it rod's ability to ward off corrosion once it has achieved a low resistance to earth. Results show that the X-it rod's internal moisture content decreases with current passage due to heat generation and electroendosmosis. Corrosion occurs rapidly, and massive destruction is evident.

The single largest concern in ground bed corrosion is severe necking. Necking refers to the increased corrosion at or near the soil surface. This phenomenon is due to the upsweep of corrosion products and lack of adequate oxide protection. If left unchecked, certain rods tend to sever at the soil surface, thus breaking the vital ground connection. Therefore even though a substantial amount of metal is left in contact with the earth, no ground connection is present.

ACKNOWLEDGMENT

The authors wish to thank the Bureau of Mines for funding this research effort under grant G0144138. Special thanks go to Airco Speer Graphite Division, Duriron Co., and X-it Rod Corp. for their kind donation of grounding material.

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A CONTINUOUS GROUND BED RESISTANCE MONITOR

by

R. Sainath[1] and Wils L. Cooley[2]

ABSTRACT

Continuous monitoring of ground bed resistance is essential to insure a low-resistance path for fault currents, lightning strokes, and electrostatic discharges. This paper explains the salient features of the continuous ground bed monitor and its applications. The importance of a low-resistance path to ground is highlighted. Sample readings obtained with the ground bed monitor are included, and typical applications of this instrument are illustrated.
This effort was supported by the U.S. Department of Interior's Bureau of Mines under USBM grant G0144138.

INTRODUCTION

The ground bed is an important safety feature in every mine power system. All machine frames are intentionally connected to the safety ground bed to provide a low-resistance path to ground for abnormal currents resulting from lightning strokes, static charge accumulation, and system faults (such as line-to-neutral or line-to-line faults) that induce current flow into the ground. The ground system is thus maintained at earth potential by intentionally connecting it to the safety ground bed. The ground bed is simply a geometric arrangement of metal rods driven deep into the earth and interconnected to yield a low equivalent resistance.

CHARACTERISTICS OF A MINE POWER AND GROUND SYSTEM

A typical mine power system and the corresponding mine ground system are illustrated in figures 1 and 2, respectively. The figures reveal the mine ground system to be a tree structure, with several branches from each tie point. Closed loops are notably absent, thus eliminating large current flow induced by nearby currents.

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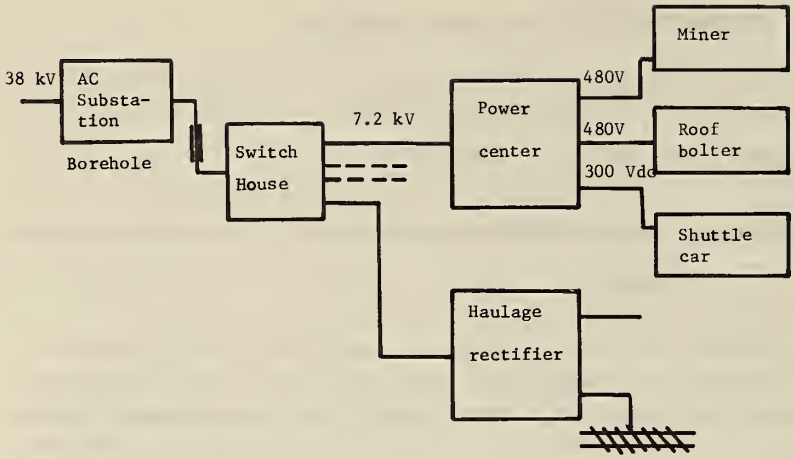


FIGURE 1. - Basic mine power system.

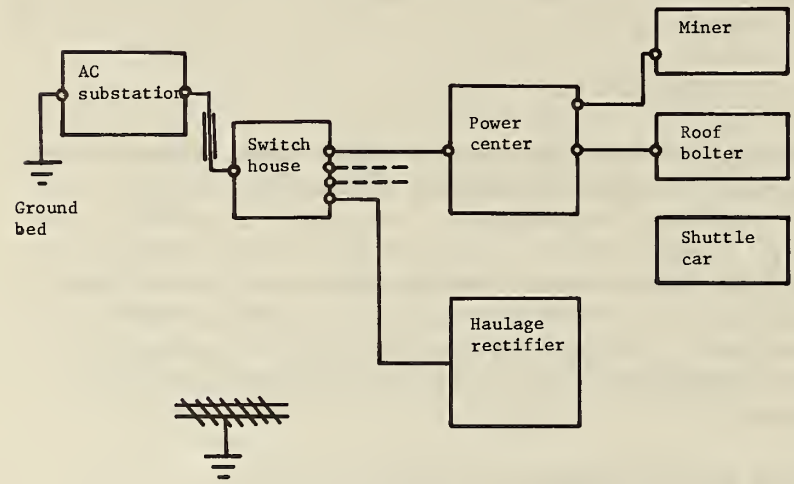


FIGURE 2. - Basic mine ground system.

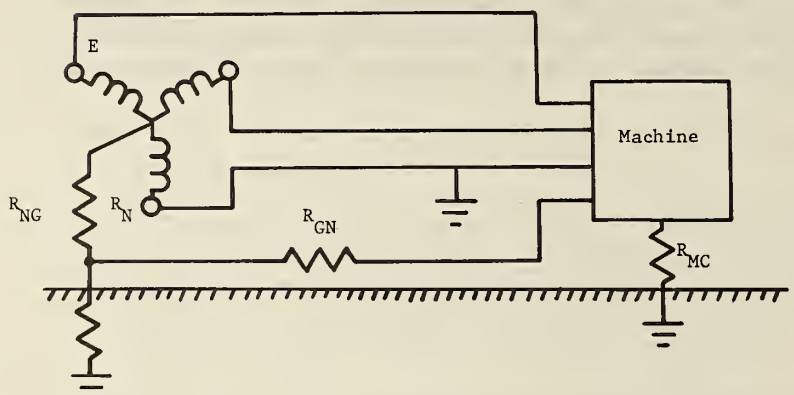


FIGURE 3. - Example of a ground system for an electrical machine.

IMPORTANCE OF MONITORING A LOW-RESISTANCE GROUND

The absence of a low-resistance path for fault currents will create hazardous situations. Consider figure 3, which shows a machine resting on the earth's surface. The three-phase supply to this machine is from the substation transformer secondary whose neutral is connected to the ground bed through resistor R_N. The ground bed resistance is denoted by R_G. The machine frame is connected to the safety ground bed via a ground wire whose resistance is denoted by R_{GN}. The contact resistance between the machine frame and ground is denoted by R_{MC}. From figure 4 the current distribution can be found. An operator standing on the ground and touching the machine frame will experience a touch potential across his body. The machine-frame-to-earth potential can be determined by mesh or node circuit analysis.[3] Assuming a line-to-line supply voltage of 6,160 volts and typical values of 100 ohms for R_N and 2 ohms for R_{GW}, the frame-to-earth potential can be determined as a function of ground bed resistance R_G for different values of machines-contact resistance R_{MC}. The results of this analysis are shown in graphical form in figure 5.

[3]An expression for the frame potential is derived in the appendix.

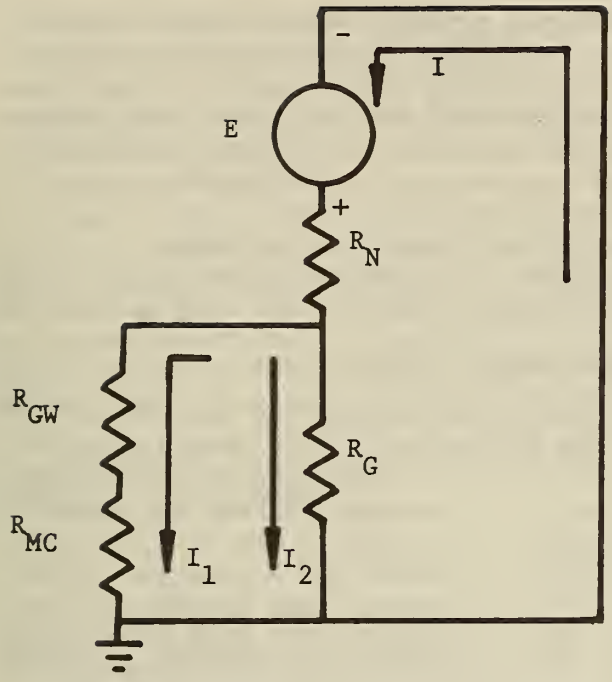


FIGURE 4. - Equivalent circuit of figure 3 under line-to-ground fault condition.

Two interesting features of the graph are immediately apparent:

1. At low values of ground bed resistance, the frame potential changes very rapidly with changes in ground bed resistance. As bed resistance increases, the curve gradually flattens out, and in the limiting case ($R_g \rightarrow \infty$) the frame potential is the voltage drop across R_{MC} in the potential divider network consisting of R_{MC}, R_{GW}, and R_N. A low value of R_{MC} will considerably lower the magnitude of this limiting value. For example, for a high ground bed resistance of 100 ohms, the frame potential is 192 volts for a machine-contact resistance of 10 ohms, but jumps to 590 volts for a machine-contact resistance of 50 ohms.

2. At low values of bed resistance, the frame potential does not change significantly with change in machine-contact resistance. As the ground bed resistance increases, there is a significant change. For example, the frame potential changes from 33.72 volts to 43.62 volts for a change in R_{MC} from 10 ohms to 50 ohms and for R_G equal to 2 ohms. When R_G is increased to 5 ohms, the frame potential increases from 68.21 to 100.71 volts for the same change in R_{MC}. At still higher values of R_G the change is still higher.

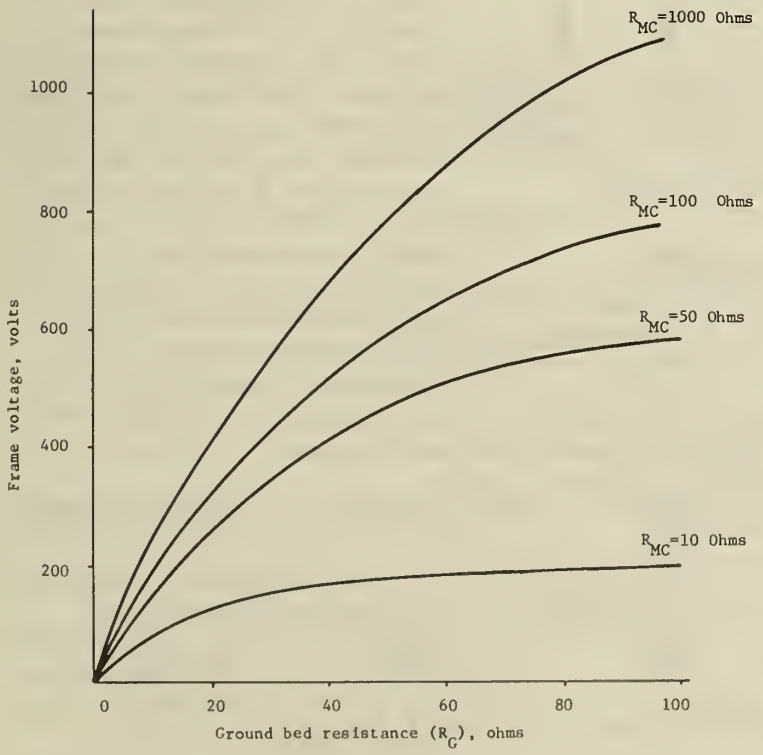


FIGURE 5. - Plot of frame voltage versus bed resistance for various values of machine contact resistance.

From the above analysis, one may conclude that ground beds should be designed for a very low resistance. Stationary electrical equipment should be properly installed so that the frames have good electrical contact with the earth.

Considerable attention is therefore being given to insure that a low-resistance path is always maintained, not only while designing and constructing the ground bed but also by periodically checking its resistance. The ground bed monitor described in this paper is designed for the continuous measurement and record of ground bed resistance. Its all-electronic circuitry includes several notable features. Integrated circuit operational amplifiers have been used for realization of all the major circuit functions. The monitor can withstand a wide range of ambient conditions and is compact and portable. Plug-in terminations enable it to be easily installed. A step-by-step procedure for calibration, installation, and maintenance of the monitor has also been documented.

OPERATING PRINCIPLE OF THE GROUND BED MONITOR

Measurement of ground bed resistance using the ground bed monitor is based on the fall-of-potential method. The principle of this method consists of injecting an alternating current between the ground bed and a remote auxiliary electrode A as shown in figure 6. The ground bed auxiliary electrode spacing should be sufficiently large to reduce the mutual coupling between the ground bed and electrode A to an insignificant level. An accepted rule-of-thumb puts this spacing at six to seven times the largest dimension of the ground bed. Another electrode, B, is interjected between the ground bed and the remote auxiliary electrode. The spacing between electrode B and the ground bed is 61.8 pct of the distance between electrode A and the ground bed. The voltage-current ratio is a measure of the ground bed resistance.

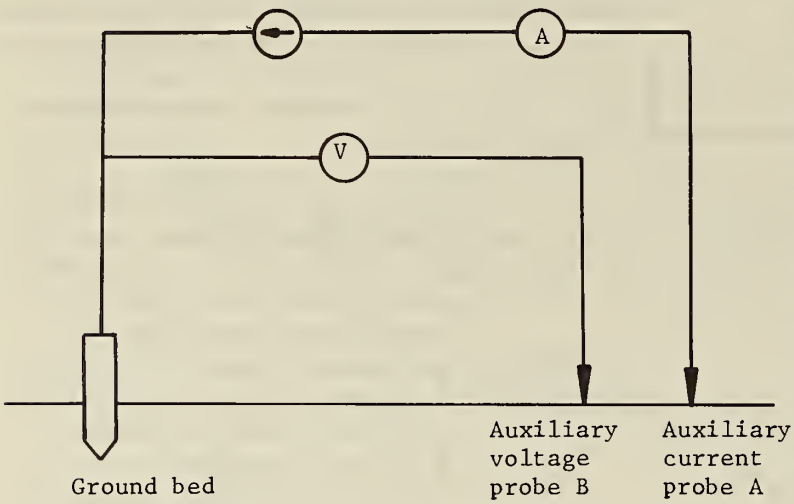


FIGURE 6. - Fall-of-potential principle.

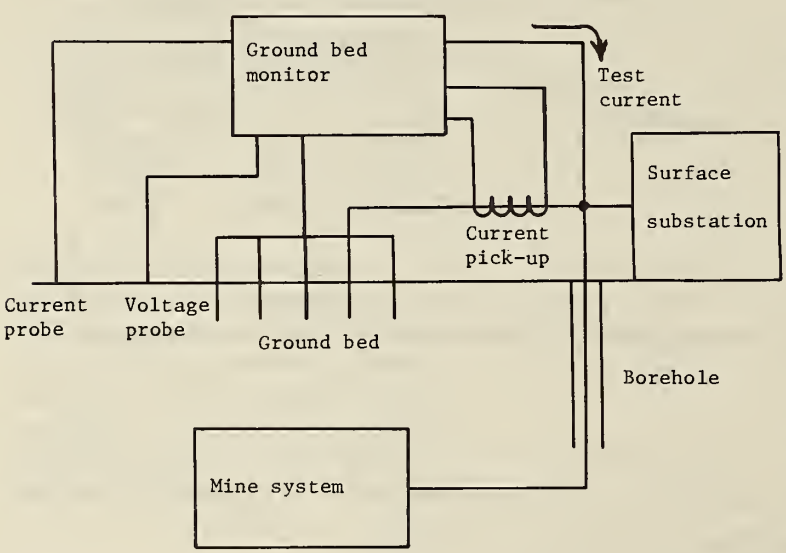


FIGURE 7. - Typical application of the ground bed monitor.

PRACTICAL CONSIDERATIONS

In principle, the measurement of ground bed resistance looks deceptively simple. In practice it is not so, for the reasons mentioned below:

1. Figure 7 shows a typical application of the

ground bed monitor. A fraction of the injected current is picked up via a current transformer installed in the current return path around the cable linking the ground bed to the station ground. A large fraction of the injected current is diverted to the mine ground. The pickup current is thus greatly reduced in magnitude and requires special circuitry for its measurement and for noise suppression.

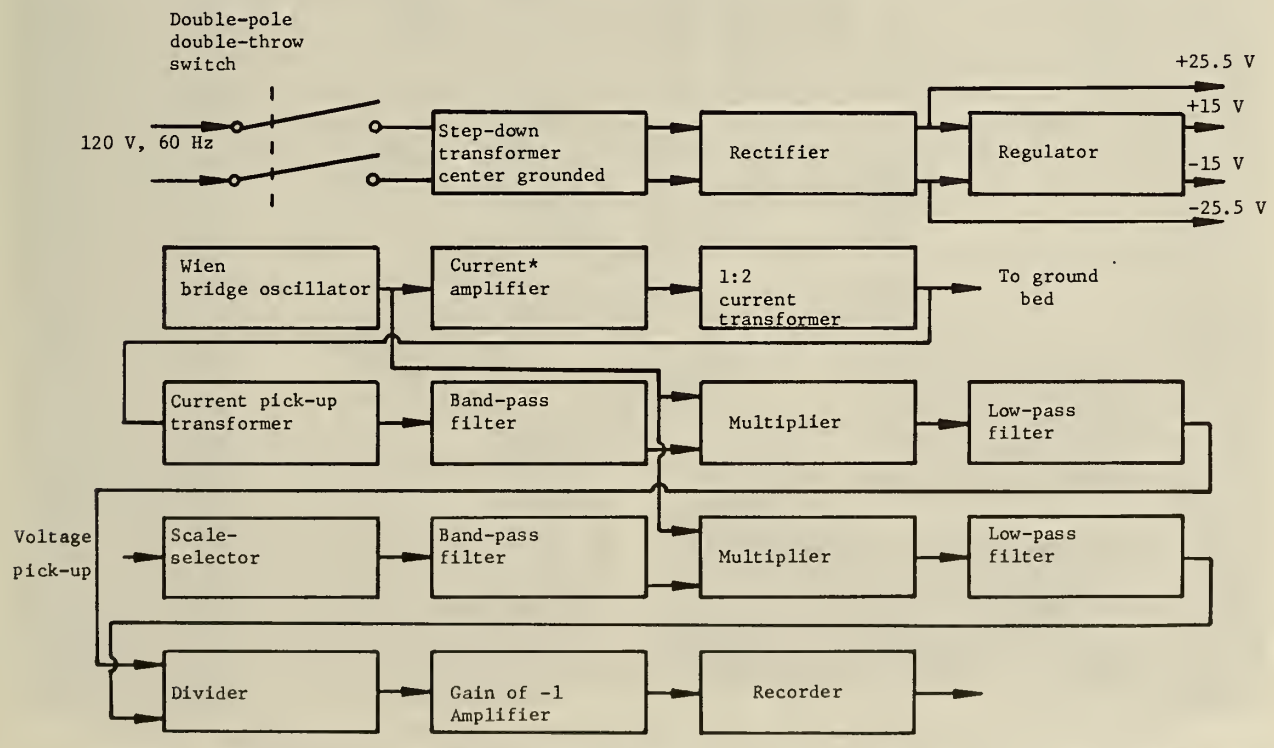
2. Another problem is the stray pickup common to all electrical measurements in grounding systems. The earth is a sink for an almost infinite variety of currents and voltages, and these constitute stray pickup by the voltage electrode described in figure 6, in addition to the voltage signal corresponding to the injected current. Isolation of the voltage signal from the stray pickup again requires special circuitry.

The final prototype of the ground bed monitor takes into account these practical requirements.

SCHEMATICS

Figure 8 is a block schematic of the circuitry used in the ground bed monitor. Broadly this circuitry can be classified under five groups:

1. Power supply: This generates ±15 volts dc and ±25.5 volts dc for the monitor circuitry. This is accomplished by stepping down the 120-volt ac



*±25.5 V supply for current amplifier. Unless otherwise specified, all the other circuits have ±15 V power supply.

FIGURE 8. - Block schematic of circuitry.

supply, rectifying it, and feeding the rectifier output to a voltage regulator circuit to obtain a regulated ±15-volt supply.

2. Current source: This is accomplished by generating a 11-Hz sinusoidal voltage signal by means of a Wien bridge oscillator and feeding this signal into a voltage-controlled current source for current amplification. This is further stepped up by a 1:2 transformer before injection into the ground. The 11-Hz frequency is chosen as a practical compromise to avoid polarization effects created by dc signals and harmonic-subharmonic pickup of 60-Hz signals.

3. Current pickup: The small fraction of the injected current picked up by the current transformer is fed to a band-pass filter for first-stage filtering and then to a synchronous detector circuit. This is a phase-sensitive circuit and by comparison of the pickup signal with an 11-Hz reference signal, it attenuates any stray signals and generates a dc output proportional to the injected signal.

4. Voltage pickup: After passing through a scale selector for appropriate range selection, the voltage pickup signal is fed to a band-pass filter for first-stage filtering and then to a synchronous detector whose function is exactly the same as in the current pickup circuit. A dc signal proportional to the voltage pickup signal is generated.

5. Divider: The current and voltage output signals described above are further filtered through low-pass filters for eliminating ac signals. The filtered outputs are then fed into a divider circuit whose output is the ratio of the two inputs and equals the ground bed resistance to a certain scale. The signal is fed to a calibrated strip-chart recorder through a scaling amplifier. The pointer deflection will depend on the input signal and is a measure of the ground bed resistance.

CALIBRATION AND INSTALLATION

The following calibration checks are made in the laboratory prior to the installation of the ground bed monitor:

1. DC power supply.

2. Oscillator signal magnitudes.

3. Current source magnitude.

4. Offset adjustments for the filters and multiplier.

5. Offset adjustments for the divider.

Installation procedure for the monitor is simple and straightforward. The auxiliary current probe is an 8-foot ground rod driven into the earth at a distance of six to seven times the largest dimension of the ground bed. The

voltage probe is a 1-foot rod driven in at 61.8 pct of the ground bed-current electrode distance. The current pickup transformer is hooked through the cable linking the safety ground bed and the system ground. The leads from the current transformer, current probe, voltage probe, and ground bed are connected to a six-pin plug to match the six-pin socket connections from the output terminals of the monitor. When these are plugged together and the power supply is switched on, the monitor is ready for use.

CONSTRUCTION AND GENERAL APPEARANCE

Figure 9 shows the general appearance of the ground bed monitor. The monitor circuitry is housed in a compact, weatherproof box. The system is designed for a 120-volt, 60-Hz supply. The electronic hardware has been assembled on five printed circuit boards. The component and printed circuit board layout has been designed for easy accessibility. All incoming and

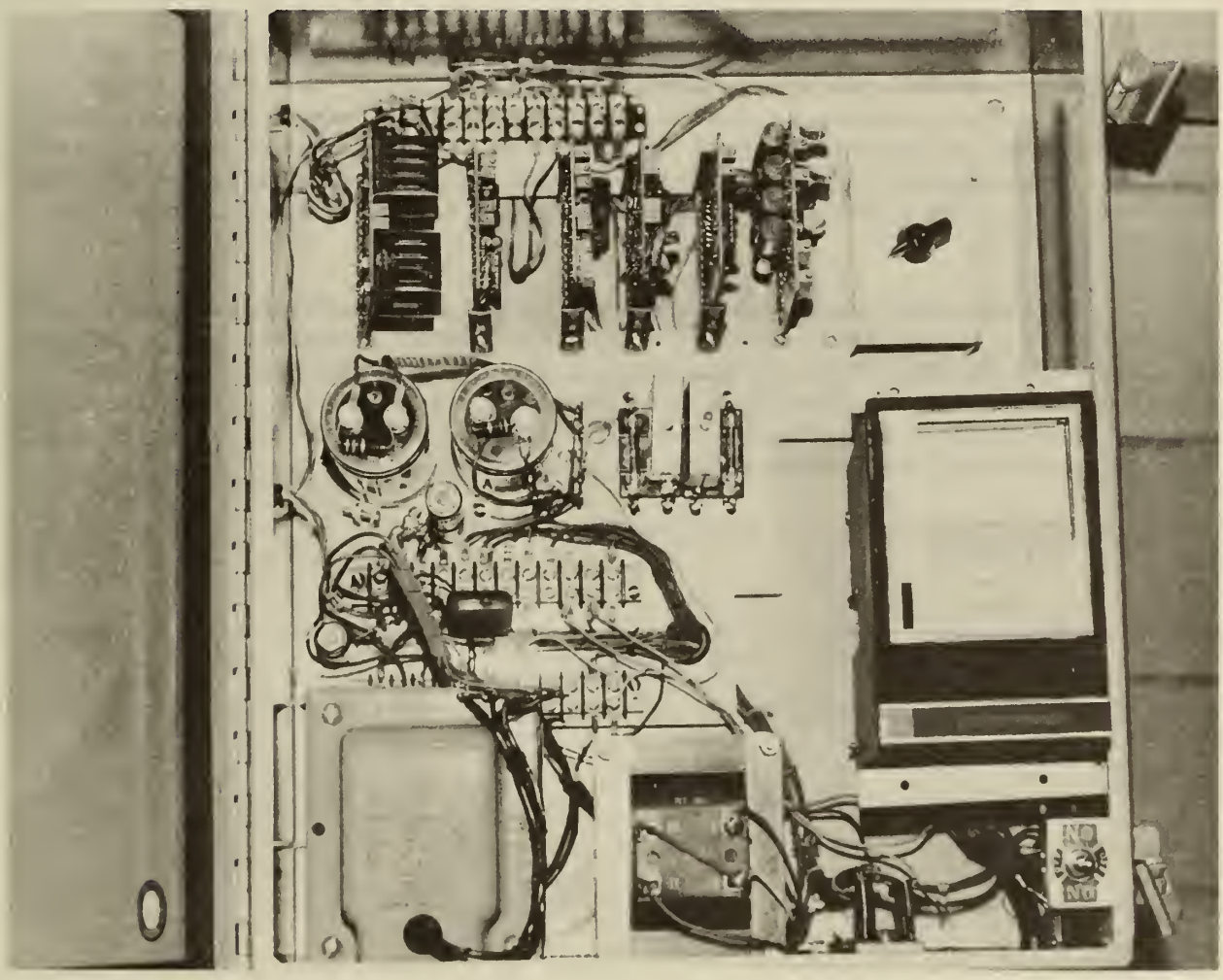


FIGURE 9. - General appearance of the ground bed monitor.

outgoing leads have been tagged for easy identification. Major interconnections have been terminated in three terminal strips as below:

1. Leads to ground bed, current pickup, current electrode, and voltage electrode.

2. Power supply.

3. Connections to instrument transformer and recorder.

The leads to the ground bed, current pickup, current electrode, and voltage electrode are terminated in a six-pin socket to match the incoming field connections which are terminated in a six-pin plug.

APPLICATIONS

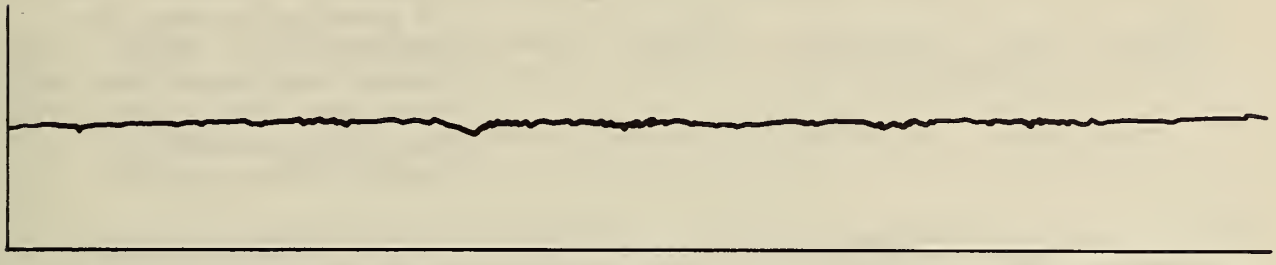
1. When properly installed, the ground bed monitor can measure and record the ground bed resistance almost uninterruptedly. The chart rolls will need periodic replacement. A continuous record of the ground bed resistance can throw light on several aspects of grounding. Resistance changes due to weather, temperature, and ground rod corrosion can be detected from the recorded data. The effects of surge currents on ground bed resistance can also be studied.

2. Another important application is the detection of ground conductor failures. The ground bed conductor links the station ground to the ground bed. An accidental disconnection of the station ground from the ground bed can result in abnormal potential rise with respect to ground if a system fault occurs. An operator standing on the ground may be subjected to a severe shock when he touches any substation equipment or mining equipment.

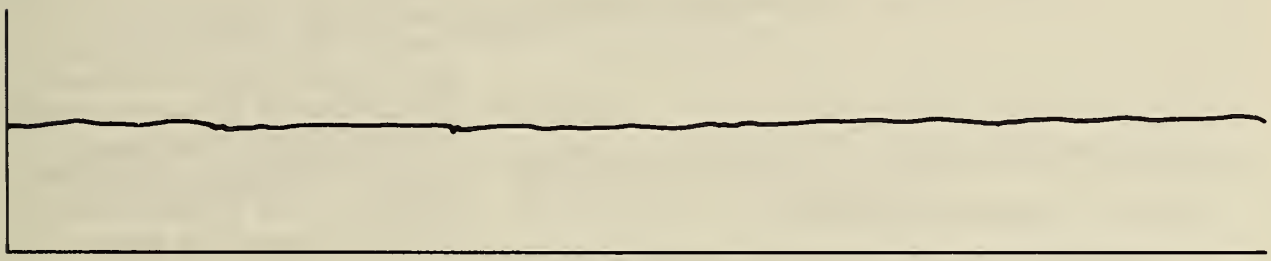
RESULTS

The monitor was field-tested on several occasions. Listed below are some of the results obtained.

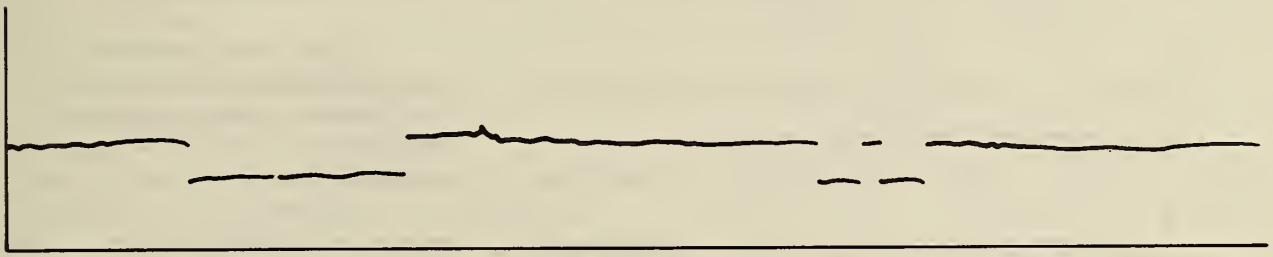
1. Figure 10 shows three continuous traces obtained with the ground bed monitor. The readings were recorded at a coal mine in Delmont, Pa.



Friday, April 2, 1976

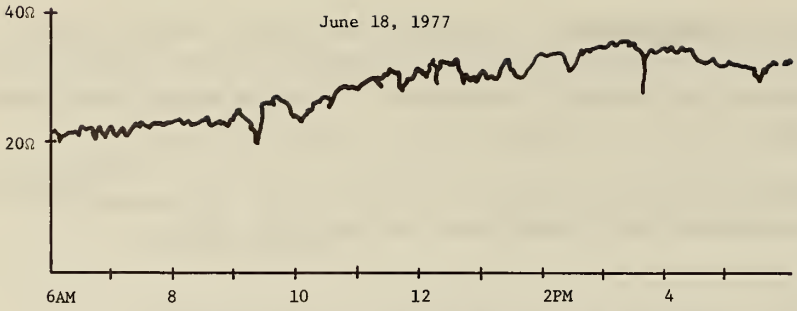


Sunday, April 4, 1976

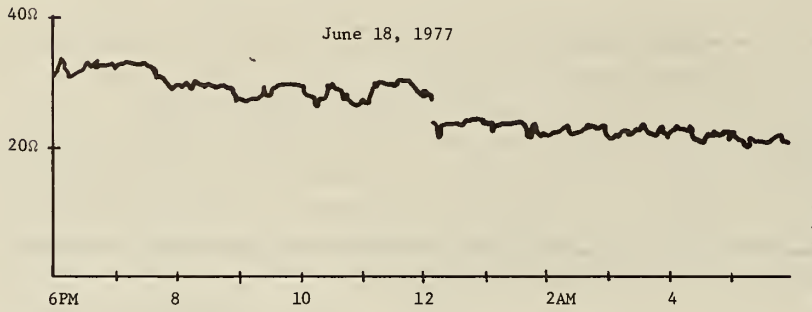


Sunday, May 9, 1976

FIGURE 10. - Sample data from ground bed monitor.



Tracing #5: resistance tracing following early morning rain storm, which lasted from 6AM to 10AM.



Tracing #6: second portion of tracing #5.

FIGURE 11. - Tracings taken with the ground bed monitor.

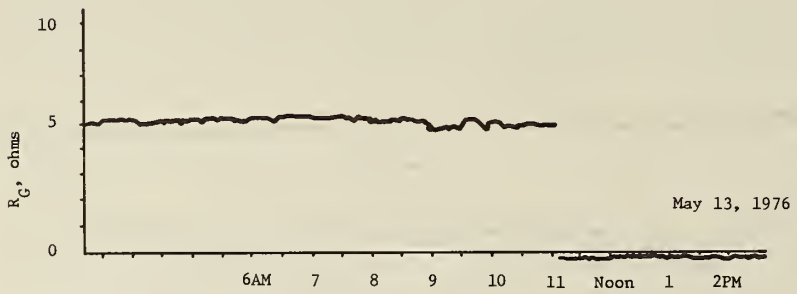


FIGURE 12. - Tracing illustrating a typical application of the ground bed monitor in detecting ground conductor failures.

2. Figure 11 shows two traces of ground bed resistance taken during and after a rainstorm. The traces show a significant increase in ground bed resistance during the rainstorm and a decrease thereafter. This is contrary to what one would normally expect. This proves that unresolved factors about mine power grounding exist and merit a detailed investigation.

3. Figure 12 shows a typical application of the ground bed monitor in detecting ground conductor failures. This trace, obtained at a coal mine in Delmont, Pa., shows a sudden decrease of the pointer reading to zero. Inquiries revealed a break in the ground conductor at about this time.

CONCLUSIONS

Mine power system grounding is a subject of continuous investigation. Theoretical and experimental studies have yielded valuable information and improvements in ground design. The ground bed monitor is a useful aid in experimental research which can complement theoretical studies. As investigations continue and new research areas are identified, the applications of the ground bed monitor are expected to grow.

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APPENDIX.--DERIVATION OF AN EXPRESSION FOR FRAME POTENTIAL FOR A LINE-TO-EARTH FAULT

From figure 5 the total equivalent resistance of the circuit is

$$R_N + \frac{R_G (R_{MC} + R_{GW})}{(R_G + R_{GW} + R_{MC})} .$$

The current I flowing in the loop is equal to $\frac{E}{R_N + \frac{R_G (R_M + R_{GW})}{(R_G + R_{GW} + R_{MC})}}$,

$$\frac{E}{\frac{R_N \; R_G (R_{MC} \; R_{GW})}{(R_{GW} + R_{GW} + R_{MC})}} \times \frac{R_G \times R_{MC}}{R_G \; R_{GW} \; R_{MC}}$$

$$= \frac{E \; R_G \; R_{MC}}{R_N (R_G + R_{GW} + R_{MC}) + R_G (R_{MC} + R_{GW})} .$$

Assuming E_{LL} = 4,160 volts (or $E_{L-N} = \frac{4,160}{\sqrt{3}}$ = 2,401 volts),

R_N = 100 ohms,

R_{GW} = 2 ohms,

$$V_{FRAME} = \frac{2,401 \; R_G \; R_{MC}}{102 \; R_G + 100 \; R_{MC} + 200 + R_G \; R_{MC}} .$$

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